THE UNIVERSITY OF ALBERTA

HYDROCYCLONE THICKENING WITH THE AID OF FLOCCULANTS

A Thesis

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by

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ABSTRACT

Tests carried out with both kaolin and silica slurries show that flocculants of the polyacrylamide type can be used to improve the thickening performance of hydrocyclones. This thickening improvement demonstrates that contrary to previously held theories, flocs can be formed which are capable of resisting the shear forces in a hydrocyclone.

For the 1.25-inch diameter cyclone used, optimum thickening occurs when the flocculant solution is injected into the slurry stream at or near the feed inlet. From hydrocyclone retention time considerations, the time required for polyacrylamide flocculants to form flocs in a turbulent flow stream is found to be less than 0.3 seconds.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

LIST OF FIGURES

HYDROCYCLONE THICKENING WITH THE AID OF FLOCCULANTS

INTRODUCTION

All hydrometallurgical processes require the separation of solid particles from aqueous solutions during various stages of the operations. Three general types of unit operations are used to effect such separations. These are: thickening, filtering, and drying. Thickening, or clarification if the solution is the ultimate product, is the most economical means of making a liquid-solid separation provided recovery of all the solution is not required.

In thickening operations, the settling rate of the smallest particle to be recovered is the important controlling factor in determining the size of the unit. Similarly, in filtering operations the fine particles, or slimes, tend to render the filter cake impermeable, drastically reducing the filtration rate. One method used to overcome the problems involved in handling the fine particles is the use of flocculants. Flocculants promote the coalescence of separate particles into clusters or flocs. The resulting flocs have the settling and filtering characteristics of large particles. Thus by increasing the effective size of the particles through flocculation, the size of filtering and settling units can be substantially reduced.

Up until the present, hydrocyclones have been used primarily for classification and mineral beneficiation. Hydrocyclones have not been widely accepted as thickeners because of their inability to efficiently

separate very fine solids, of say less than 5 microns, from the suspending solution. To separate the fine material, gravity thickeners can utilize the beneficial effects of flocculation, whereas in the hydrocyclone it was always assumed that the existence of shear would break up and prevent the formation of flocs. Thus if no floc structure can be retained, the hydrocyclone would have to be designed so that its separation size would be below the size of the smallest particle to be recovered. To obtain a very small separation size requires the formation of very high centrifugal forces, which at normal pressures, necessitates the use of small diameter cyclones. Small hydrocyclones have, in turn, very low throughput capacities which renders them impractical for many industrial thickening applications. Thus if the effects of flocculation can not be utilized, the usefulness of hydrocyclones as thickeners is limited.

In the past few years, new and extremely powerful flocculating agents have appeared on the market. These chemicals are capable of forming flocs which are much more stable and shear resistant than those formed by the standard flocculants used in the past. The object of this work, the results of which are reported in this thesis, was to determine whether these new flocculating reagents can be used to enhance the use of the hydrocyclone as a thickener and, secondly, to investigate how these reagents should be added for optimum results.

OUTLINE OF HYDROCYCLONE THEORY

1. General Description

The hydrocyclone is a piece of equipment which utilizes fluid pressure energy to create rotational fluid motion. In operation a suspension of materials to be separated is introduced under pressure through an inlet in the upper portion of the device. The vessel at the point of entry is usually cylindrical. It may remain cylindrical over its entire length, although it is more usual for it to become conical. Due to the tangential inlet, a rotational motion is established throughout the cyclone.

Many variations in the design of hydrocyclones exist. The relative insensitivity to changes in design has, for years, allowed satisfactory operation of cyclones designed on empirical test data rather than theoretical analysis. A generally accepted arrangement of the hydrocyclone components, as illustrated by Lilge[1], is shown as Figure 1. This discussion will be limited to this "normal" hydrocyclone.

As shown in Figure 1A, two outlets concentric with the cone axis are provided--the underflow and the overflow. The underflow is located at the bottom of the conical section and the overflow at the top of the cylindrical portion. A cylindrical shield, termed the vortex finder, is placed around the overflow and extends down to a point below the level of the inlet orifice. The normal relationship between the inlet diameter, overflow diameter and cone diameter is $Di = Do = Dc/6$. The underflow is normally made large enough to freely pass all the solids discharged.

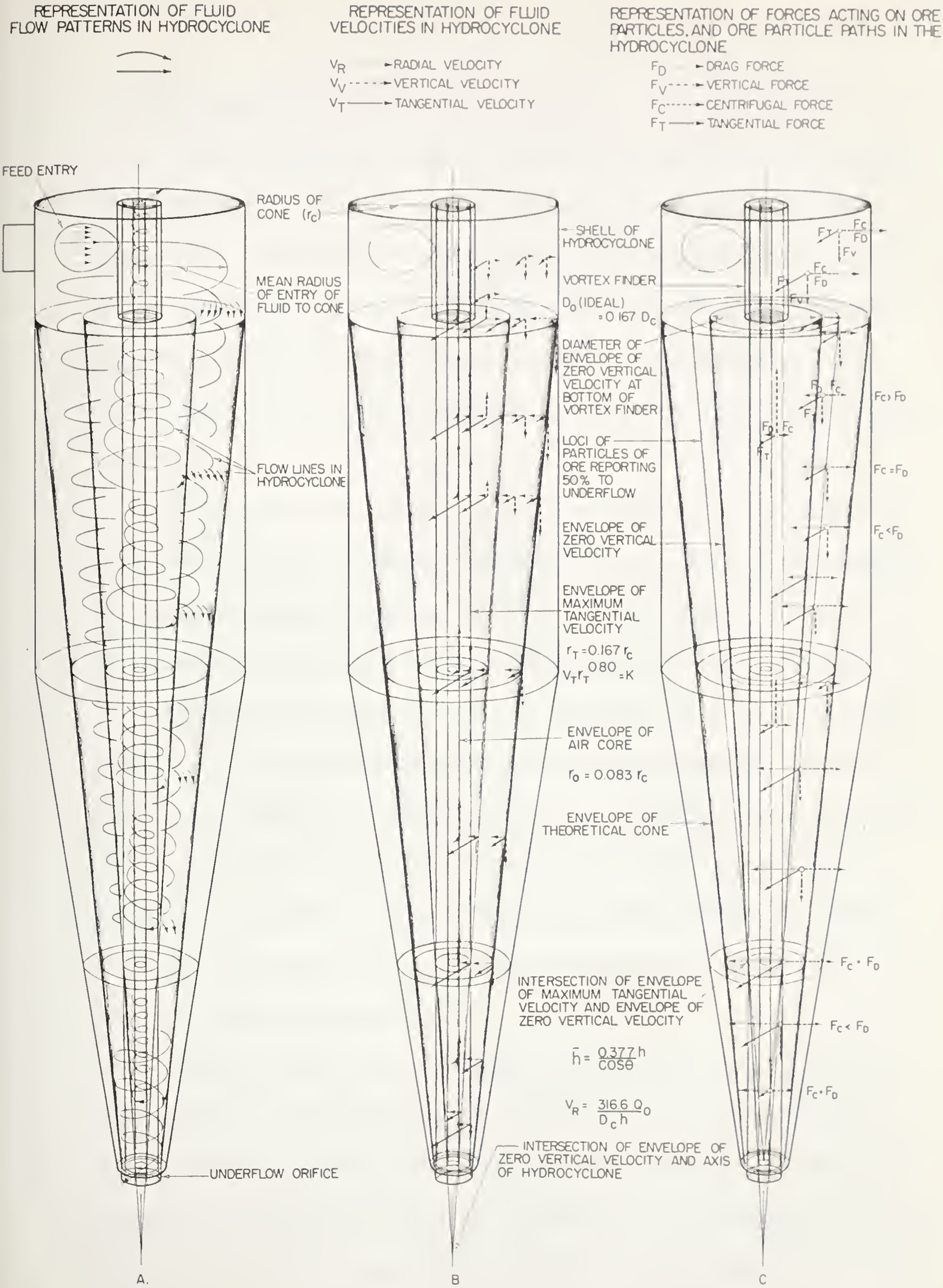

FIG. 1 — FLUID FLOW PATTERNS, FLUID VELOCITIES, FORCES ACTING ON ORE PARTICLES AND ORE PARTICLE PATHS IN THE HYDROCYCLONE (AFTER LILGE).

2. Flow Patterns

Since both outlets are located below the level of the inlet, a downward component of velocity is imparted to the slurry after entry (See Figure 1A). As the material moves downward to a point below the level of the vortex finder, some of the medium begins to reverse its direction and flow upwards towards the overflow orifice. Thus along the outer section the flow is spiraling downwards and near the centre it is spiraling upwards.

Due to the vortex motion, large centrifugal forces are developed, which tend to keep the particles with high settling velocities concentrated near the periphery of the cone. As the flow in this region is downwards the solids are discharged at the underflow as a thickened suspension.

Because both outlets are located concentric to the cone axis, the medium must all advance towards the axis before escaping. The fluid drag forces created by this radial component of velocity acts in opposition to the centrifugal forces on the solid particles. Thus no particle can report to the overflow unless the fluid drag forces caused by the radial component of velocity, exceeds the centrifugal forces caused by the tangential component of velocity.

Because of the complex nature of the fluid flow patterns within the hydrocyclone, most experimental work reported in the literature has been confined to specific applications of the hydrocylone. The first real quantitative analysis of the flow patterns was carried out by Kelsall[2] in 1952. Kelsall measured the tangential and vertical velocity components in a 3-inch

[illegible]

[illegible]

[illegible]

[illegible]

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diameter cyclone using a microscopic technique. From continuity considerations, the radial velocity components were determined. Since then, Yoshiota and Hotta[3], Bradley[4], Tarjan[5] and Lilge[1] have expanded the knowledge of the flow patterns within the hydrocyclone. While the general concepts have now been well established, a precise prediction of the flow patterns over a wide range of design variables is not yet possible.

3. Tangential Velocity Component

In a free cylindrical vortex of a perfect fluid it is known that due to the conservation of angular momentum, the velocity-radius relationship is:

$$V_t R = \text{constant}$$

Viscous forces however tend to prevent velocity differential between adjacent layers. When the velocity differential is zero, as in a forced vortex, the relationship between velocity and radius is V_t/R = constant. From theoretical considerations it can be stated that $V_t R^n$ = constant, where "n" must be between minus one and plus one.

Kelsall in his detailed study showed that the loci of constant tangential velocity were cylindrical and that the velocities were independent of the level in the cyclone. This has been verified in later work by Bradley, Lilge and Tarjan.

It was further found that the tangential velocity increases with decrease in radius until a maximum is reached near the cone axis at a radius of about one sixth of the cone radius. At a radius less than one sixth of the cone radius, the velocity decreases proportionately with

further decrease in radius. Along the cone axis there is no fluid. The low pressure region formed by the vortex action sucks in air which leads to the establishment of a cylindrical air core extending the full length of the cyclone. The diameter of this air core is given by Lilge as being about one twelfth of the cyclone diameter.

Many investigators have determined the value for "n" between the cone wall boundry layer and the radius of maximum tangential velocity. Most values fall into the range of 0.75 to 0.85 for normal cyclone operations. An average value of 0.8 is generally accepted unless cones of very small apex angles or diameters are used. Tarjan in his mathematical analysis[5] concluded that "n" increases with inlet diameter and cone angle, and is not affected by either the size of the outlets or the feed pressure. In practice, the formula generally used for velocity calculations is:

$$V_t R^{0.8} = \text{constant} \qquad (1)$$

To predict the tangential velocity at any point, a relationship between tangential velocity and inlet velocity must be used. Kelsall found that as the liquid enters the cyclone there is a drop in velocity. A ratio of the velocities is normally given the symbol β, and is defined as:

$$\beta = \frac{V_{te}}{V_i} = \frac{\text{Tangential Velocity at the average radius of entry}}{\text{Bulk inlet velocity}}$$

Lilge established an emperical relationship between β and A_i/A_c. The relationship is as follows:

$$\beta = 5.31 \left(\frac{A_i}{A_c}\right)^{0.565} \qquad (2)$$

This formula together with formula (1) can be used to calculate the tangential velocity component in the hydrocyclone.

4. Vertical Velocity Component

As already mentioned the vertical component of velocity in the outer region of the hydrocyclone is downward, while in the inner region of the hydrocyclone the velocity is upwards (assuming cone is in vertical position with apex pointing downwards). This difference in flow direction results in an area of zero vertical velocity, which forms the boundary between these two regions. From Kelsall's velocity profiles it is seen that loci of zero vertical velocities form a conical shaped envelope within the cyclone, with its base at the level of the bottom of the vortex finder. Bradley[6] in studying the flow patterns with dye injections found that the envelope of zero vertical velocity was cylindrical in shape in the cylindrical portion of the hydrocyclone, and assumed a concial shape only in the conical section. He attributed the conical shape of the envelope, obtained by Kelsall, to the fact that Kelsall's vortex finder extended well into the conical section of the cyclone, so that the cylindrical shape of the upper section did not manifest itself in his tests. Lilge in his work based his assumptions on Kelsall's findings in assuming a conical shaped envelope of zero vertical velocity. Lilge defined the envelope as being "the loci of a line joining the mid-point at the vortex-finder level with a point on the circumference of the air core at the level of the underflow orifice". This is illustrated in Figure 1. The shape and size of the envelope of zero vertical velocity is important since this is the basis upon which the radial velocity component is calculated.

5. Radial Velocity Component

The radial component of velocity in the hydrocyclone ranges from 0 to 4 percent of the tangential component. Because it is small compared to the tangential component, no direct measurement of the radial component has been accomplished. Kelsall by measuring the tangential and vertical components throughout the cyclone was able to establish the radial component velocity profiles throughout the cone from continuity considerations.

Kelsall found that the radial component, V_r, is maximum near the conical wall and decreases to zero as the air core is approached. He found that the radial component is related to the vertical component, V_v, as:

$$V_r = V_v \tan\left(\frac{\theta}{2}\right)$$

where θ is the apex angle. Using the radial velocity profiles from Kelsall, Lilge found that the radial velocity was zero on the envelope of zero vertical velocity at the level of the bottom of the vortex finder. He further observed that the radial velocity across the conical envelope of zero vertical velocity increases as a linear function of the distance below the level of the vortex finder. From this it is possible to establish a height where the radial velocity is equal to the average velocity as found by dividing the overflow rate by the total curved area of the envelope of zero vertical velocity. Thus by assuming that all the flow crossing the envelope of zero vertical velocity passes to overflow, a radial velocity can be found at any point along the envelope of zero vertical velocity in terms of the cone dimensions and overflow rate. At the intersection of the envelope of zero vertical velocity and maximum tangential velocity, the radial velocity, V_r, in terms of cyclone

diameter D_c, overflow Q_o, and cone height, h, is:

$$V_r = \frac{2.219\, Q_o}{D_c h} \tag{3}$$

Bradley in his tests found that the radial velocity across the cylindrical portion of the envelope of zero vertical velocity was zero. He found that dye, when injected into the cone as a burst, would remain in this region long after the remaining regions had cleared themselves of dye. This indicates that in this region, which he termed a "mantle", the vertical and radial velocity components are both zero. Bradley therefore assumed that all the radial flow took place below the mantle over the conical portion of the envelope of zero vertical velocity which he termed the classification surface. By dividing the volumetric flow rate to the overflow by the classification surface area he was able to calculate an average radial velocity. Bradley's equation expressed in the same terms as Lilge's equation becomes $V_r = \frac{4.22\, Q_o}{hD_c}$. As will be noted, the constant is higher than that used by Lilge because the surface area assumed for the derivation was smaller.

6. Pressure Drop Across a Hydrocyclone

A large number of investigators have studied the relationship between pressure drop and flow rate in a hydrocyclone. Many relationships have been developed, most of them of a quasi-theoretical nature. One of the earliest and most widely used is the Dahlstrom equation[4], which has the following form:

$$Q = K(D_o\, D_i)^{0.9} \cdot (H)^{0.5}$$

In the formula, Q is the throughput rate in U. S. G. P. M. , K is a constant the value of which is dependant upon cone variables such as cone angle and cone height. This constant varies from 5. 5 to 7. 0, being higher with small cone angles. D_o and D_i are the overflow and inlet orifice diameters. H is the pressure drop in feet of fluid.

It is interesting to note that the cone diameter is not included in the Dahlstrom formula. This term is included indirectly in that for normal hydrocyclones $D_c \simeq 6D_i$, and variations caused by deviation from this ratio are small compared to the changes in D_o and D_i.

Chaston[7] in investigating 139 published examples of flow and pressure drop determinations, developed a simple empirical formula for estimating the capacity of a hydrocyclone. The formula is:

$$Q = 12\, A\, P^{0.5}$$

In the formula, Q is the flowrate in USGPM, A is the area of the inlet opening in in.^{2}, and P is the pressure drop in psi. Chaston states that the formula is accurate to within plus or minus 20 percent, and as a result is only useful as a "rule-of-thumb" guide.

These formulas show that the pressure drop is close to being proportional to the velocity squared. This condition is characteristic of flow within the completely turbulent flow regime, which indicates that the flow in a hydrocyclone is turbulent under normal operating conditions.

7. <u>Volume Flow Split</u>

A hydrocyclone has one inlet and two outlets. This means that the feed volume will be split into two streams. Lilge found that when operating

with a reasonable pressure drop across the hydrocyclone and free discharge from both orifices, the flow split is a function of the relative sizes of the two outlet orifices. He termed the ratio of underflow orifice diameter to overflow orifice diameter as Cone Ratio. He relates x, the fraction of volume to overflow, to Cone Ratio graphically from experimental data.

The relative insensitivity of flow split to changes in variables other than Cone Ratio, is also verified by Tarjan, who proposed the formula:

$$x = \frac{Q_o}{Q} = \frac{1}{1 + 1.1\,(C.\,R.)^3}\;, \quad \text{where C. R.} = \frac{D_u}{D_o}$$

In the formula, Q is total volumetric flowrate and Q_o the flowrate through the overflow orifice.

8. <u>Separation Size</u>

When a suspension of solids is injected into a hydrocyclone it is assumed that the particles attain the same tangential and vertical velocity components as the fluid. Kelsall[8] states that the liquid flow patterns are not markedly affected by the presence of solids in feeds containing up to 20 percent solids by weight. Lilge found that for a fine suspension of heavy medium, the velocity profiles in the cyclone are similar to those for a newtonian fluid. Thus the relationships developed for newtonian liquids can be applied to non-newtonian slurries without serious error.

Two opposing forces affect the solid particles orbitting in the hydrocyclone: the centrifugal force caused by the rotational motion acting outwards and the fluid drag force from the radial component of the velocity acting inwards. Within the hydrocyclone a particle will seek an equilibrium

radius where these two opposing forces are equal.

If we consider an orbitting particle of spherical diameter D and density ρ_s moving with a tangential velocity V_t, at a radius R in a liquid of density ρ, the centrifugal force is:

$$F_c = \frac{\pi D^3}{6} (\rho_s - \rho) \frac{V_t^2}{R}$$

The drag force caused by the radial velocity V_R in terms of the drag coefficient becomes:

$$F_d = C_d \frac{\pi D^2}{4} \cdot \frac{1}{2} \rho V_r^2$$

At the equilibrium point the two forces must be equal, i. e. $F_c = F_d$. The expression for the diameter of the particle at equilibrium becomes:

$$D = \frac{3}{4} C_d \frac{\rho}{(\rho_s - \rho)} R \frac{V_r^2}{V_t^2}$$

If it can be assumed that the fluid flow relative to the particle is laminar i. e. Reynolds Number less than 1 or 2, then:

$$C_d = \frac{24}{Re} = \frac{24 \mu}{D V_r \rho}$$

where μ is the viscosity of the liquid. The relationship between the diameter of the particle and other variables is:

$$D^2 = \frac{18 \mu R V_r}{(\rho_s - \rho) V_t^2} \qquad (4)$$

Kelsall has shown that loci of equilibrium positions for particles of different sizes are conical in nature. It can be observed that no particle should report to overflow unless the equilibrium path of its size intersects the envelope of zero vertical velocity.

Because it is not possible to analyse the path each particle size will take, most investigators have concentrated on the D_{50} size. The D_{50} size is defined as that particle which will report 50 percent to overflow and 50 percent to underflow. The equilibrium position of this particle should be on the envelope of zero vertical velocity since this marks the boundary between the flow towards the two outlets. Lilge has shown that the loci of the particle equilibrium position and the envelope of zero vertical velocity do not coincide exactly. Therefore one point on the envelope must be chosen to represent the intersection of the equilibrium position of the D_{50} size. Lilge has chosen this to be the intersection of the point of maximum tangential velocity and the envelope of zero vertical velocity (see Fig. 1C). Bradley on the other hand argues that the point should be at the radius of the vortex finder. However for normal cyclones, $D_c = 6D_o$, which corresponds with the diameter of maximum tangential velocity.

Lilge also established a method for calculating the D_{50} size of particles of different sphericities for any flow regime, whether laminar, intermediate or fully turbulent. This treatment has the advantage over most of the methods proposed by other researchers, in that the particle shape factor is included and the calculations are not limited to the laminar flow regime.

Lilge's method also permits calculation of the D_{50} size when using non-newtonian fluids as medium, if the viscosity-shear relationship of the medium is known.

No sharp separation occurs in the hydrocyclone at the D_{50} size, since there are always some particles larger than D_{50} in the overflow and

smaller ones in the underflow. Classification curves all exhibit an "S" shape resembling a characteristic probability curve. The greater the size of particle relative to the D_{50} size, the greater the probability it will report to underflow, and vice versa.

One possible reason for imperfect classification is turbulent diffusion. Since the flow relative to the cyclone walls is normally very high, the flow must be in the highly turbulent regime as indicated from the pressure drop correlations. This would tend to oppose the concentrating effects of the centrifugal force. The instantaneous velocity fluctuations would tend to keep the particles from following their equilibrium orbits assumed above. Lilge also points out that imperfect separation is caused by the fact that particles do not enter the hydrocyclone at the same radius. A particle entering the cyclone near the wall will have less probability of reaching the overflow than a particle entering at the inner edge of the cyclone opening.

Another important factor in considering the operation of the hydrocyclone is that no positive force acts on the particles with low settling velocities to keep them from reporting to the underflow. Thus the particles much smaller than the D_{50} size will report to overflow and underflow in the same ratio as the fluid split. Because the fluid leaving the underflow will carry with it the fine particles, the underflow stream in cyclones operating as classifiers is kept as thick as possible. Another method, described by Kelsall,[8] used to minimize this effect is to inject solids-free water near the apex to displace the original fluid contained by the underflow solids.

OUTLINE OF FLOCCULATION THEORY

Flocculation is the joining together of particles in a liquid suspension. Flocculated solids exhibit the characteristics of larger particles in that they settle faster and filter better.

1. Flocculation by Electrolytes

Based on a consideration of thermodynamics it can be shown that processes will occur spontaneously if the change in free energy is negative. In a system composed of a suspension of finely divided solids the surface energy effects are significant. Considering only the change in surface energy, the general equation for free energy, F, of a system reduces to:

$$dF = TdA, \qquad \text{where } T = \text{surface tension}$$
$$A = \text{surface area}$$

When a system flocculates, the surface area will decrease resulting in a decrease in free energy. Thus, from a thermodynamic point of view, flocculation should be a spontaneous reaction.

Dispersions are kept from flocculating by the following factors:

(1) The particles adsorb specific ions on their surfaces which create a surface charge on the particle relative to the surrounding liquid. This charge, termed zeta potential, is negative for clays, silica and most sulphides. The similarly charged particles are prevented from colliding and sticking together by electrostatic repulsion.

(2) Another factor described by Schwarz et al[10] which prevents flocculation is the adsorption, or binding, of liquid or surface active agent to the surface of particles. The particles become surrounded with a protective layer of molecules which can prevent aggregation. This thin

layer is strongly adsorbed on the particle surface; hence the required work of desorption required for the particles to unite, is manifested as a repulsion. This is the action of dispersing agents added to a suspension to keep it from flocculating. However, even in systems containing no surfactants, a protective film may be formed by solvation of the particle surface. This latter type of protective film exhibits a repulsion of short range order, and is only of significance when the electrostatic repulsive forces are very low.

It is found that the addition of electrolytes generally lowers the zeta potential which lowers the electrostatic repulsive forces and allows the dispersion to flocculate. A common everyday example of electrolytic flocculation is the flocculation of milk by an acid.

2. <u>Flocculation by Polymers</u>

Lime and flour have for years been used as flocculants by thickener operators. Lime is the most economic means of introducing a bivalent cation to reduce the zeta potential of negatively charged suspensions. The role of the starch was, until recently, not fully understood. La Mer and associates[11] studied the effects of starches and other organic flocculants on the settling and filtration properties of Florida phosphate slimes. The macromolecules of starch are electrically neutral, and the clay, phosphate, and other particles in the slime are negatively charged, such that the electrical charges offered no explanation as to the mechanism of flocculation. They postulated that the effectiveness of the starch was due to the adsorptive binding of the molecule to the particle. Because of the linear shape

of the flocculant molecule it could span the gap between the particles and form a molecular bridge. The molecular bridges would then prevent the particles from moving apart. When the Brownian motion moves the particles together, other active groups on the flocculant bridge bond to the solids, holding them in closer position. The process is repeated until the particles are close together. This "bridging action" explanation for the flocculation by long chain flocculants has since been generally accepted by all investigators.

In 1954, synthetic polymers with powerful flocculating properties appeared on the market. In 1957, Evans et al[12] tested 30 different flocculants on semi-colloidal hydrated iron oxide particles in an ammonia solution. They found that a synthetic polymer* was far superior to any of the other flocculants tested.

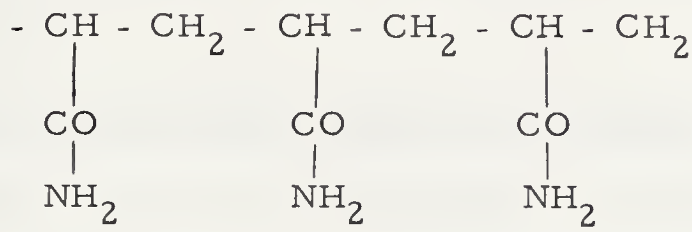
3. Molecular Structure of Polymer Flocculants

Natural and synthetic polymers can be classified as cationic, anionic and non-ionic. The polymer molecules have molecular dimensions in width, but their length may reach into colloidal dimensions. It is found that the longer the polymer, or the greater the molecular weight, the greater will be its flocculating power. With short chain polymers, the molecules tend to wrap themselves around one particle only, insulating the particle from the action of other flocculant molecules.

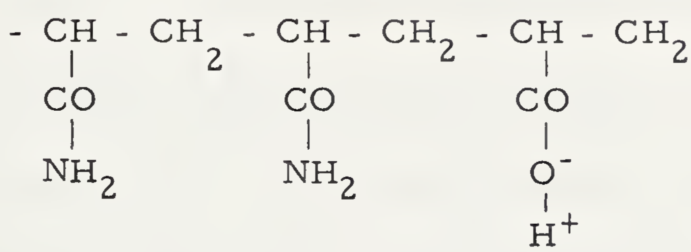
One group of synthetic organic polymers commonly used as flocculants, is the polyacrylamides. Dow's Separan, Cyanamid Aerofloc, and probably many other commercially available flocculants fall into

*Dow Chemical's Separan 2610 (now Separan NP10)

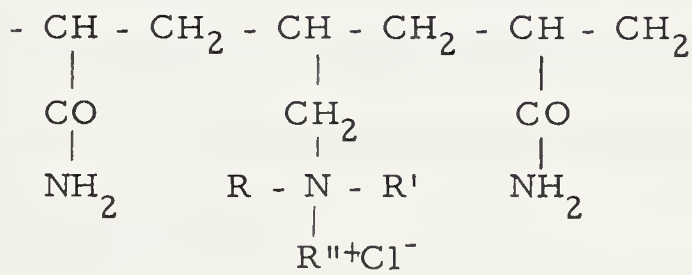
this classification. In their study of flocculants, Linke and Booth[13], formed their polymers from a pure polyacrylamide chain. The polymers were then either made anionic (negative), or cationic by copolymerizing the acrylamide with other substances. They represented the structures as shown below:



non-ionic polyacrylamide



CO^- OH^+ substituted anionic chain



amine substituted cationic group

Linke and Booth studied the actions of the different types of polymers on silica suspensions and arrived at the following conclusions:

(1) Cationic polymers are more strongly adsorbed onto the mineral surface than neutral or anionic polymers.

(2) The positive cationic polymer flocculates by neutralizing the negative surface charge of the silica.

(3) Much less of an anionic polymer can be tolerated by the silica. The negative charge of the carboxyl groups adds to that of the solid and increases the charge on the particles.

(4) The effectiveness of anionic polymers decreases markedly as the pH is raised since the surface charge of the silica increases with pH, making it more stable.

(5) The more cationic groups put on the polymer chain, the less sensitive the effect of pH will be on flocculation properties of the cationic polymers.

4. Factors Affecting Flocculation by Polymers

It has been well established that flocculation in a given solid-liquid system cannot be increased indefinitely by increased addition of flocculant. Beyond a certain "optimum concentration" the use of additional polymer often causes poorer rather than better flocculation. McCarty and Olson[14] found that the settling rate of an acid leach uranium ore pulp (16 percent solids) reached its maximum settling rate at a Separan 2610 addition of 0.23 lbs. per ton. They found that further increases of Separan caused no change in the settling rate.

Linke and Booth also investigated the effects of a number of variables on the optimum polymer/solid ratio using 85 to 100 percent minus 325 mesh silica. The results are summarized as follows:

(1) The mechanism of flocculation is relatively independent of particle size.

(2) Over a complete range of practical pulp densities (4 - 50%), the changes in optimum flocculant/silica ratio were found to be negligibly small.

(3) The isoelectric point (point of zero zeta potential) for silica is at a pH of 3.5. The optimum flocculant/silica ratio is maximum near

the isoelectric point and decreases with lower and higher pH values.

(4) As ionic strength of the solution increases, the suspension tends to flocculate due to the presence of the electrolyte. Thus the need for the polymeric flocculant decreases. The optimum flocculant/silica ratio drops rapidly to 0. 10 lbs. per ton and levels off at this value as the ionic strength increases.

According to Linke and Booth, polymers are attached to mineral surfaces by at least three distinct types of bonding.

(1) Hydrogen Bonding

Hydrogen bonding is the principal mode of attachment of polyacrylamide flocculants. In these compounds, the hydrogen atom of the polymer, because of its attachment to a strongly electronegative atom (O, N, S), has lost much of its electronic atmosphere. The hydrogen is ready to accept electrons donated by the surface atom of the solid. The hydrogen is then shared between the surface atoms (usually oxygen) and the oxygen or nitrogen of the polymer. Taken individually, the strength of this bond is relatively small, but a polymer molecule can form up to 14, 000 such bonds and the total energy of attachment per molecule is enormous.

(2) Chemical Reaction

This type of bonding occurs when the polymer forms a salt-like attachment to specific groups or sites on the solid surface. Although this type of bonding is highly energetic, it is limited to solids having metal ions in their lattices.

(3) Electrostatic Attraction

This type of interaction occurs between a charged mineral surface and an oppositely charged polymeric active site. A cationic or positively charged polymer will be attracted to the surface of a negatively charged particle and form part of its ionic double layer.

5. Flocculation by Co-precipitated Polyelectrolytes

Wadsworth and Cutler[15] studied the effects of adding a polyanionic flocculant together with a polycationic flocculant. They investigated the flocculation of Florida kaolinite clay mineral and specular hematite pulps of 15 percent solids. The cationic reagents were Peter Cooper Co. 1-X and 2-X glues which have an amine-type of active site. The anionic reagents were Monsanto's Lytron 886 and 887. The Lytron flocculants are co-polymers of acetate and maleic anhydride. They found that the best results were obtained by adding the anionic flocculant first, allowing it to come to equilibrium, and then adding the cationic polymer. The co-precipitation of the two flocculants results in the formation of large stable flocs which settle 2 to 3 times faster than those obtained with either of the two reagents used separately.

6. Effects of Agitation on Flocculation

All investigators agree that agitation is one of the basic parameters affecting flocculation. La Mer and associates[11], in their flocculation studies found that the only way to obtain reproducable results was to standardize the amount of agitation the flocculated pulp received. They found it necessary to mechanize the agitation to eliminate human differences

in inverting the settling container. In studying the effect on the number of inversions on the filtration rate, they found that an optimum was reached at about 100 inversions of the container.

It is well known that stirring accelerates the flocculations or in some instances apparently causes it. Jirgensons and Straumainis[9] report that ferric and copper oxide sols can be coagulated by prolonged agitation if air is stirred into solution. The reason for flocculation in this case is that the particles are so strongly adsorbed at the air-liquid interface, that coagulation gradually takes place.

Stamberger[16] showed that an aqueous polyvinyl disperson which had been stable for 3 years, coagulated in a few second when intense shear was applied. In his investigations, he couldn't establish any relationship between zeta potential and mechanical stability. He measured the time required for the polyvinyl dispersons to coagulate for different shear rates. For a shear rate of about 3000 sec^{-1}, the coagulation rate was 2 seconds. He cound not establish the exact reason why a stable colloidal disperson coagulates when subjected to shear.

McCary and Olson[14] in their investigations on polyacrylamides found that nearly all the flocculant is adsorbed by the solid until amounts far beyond those required for flocculation are added. This they explain, is the reason why the flocs are sensitive to more than mild agitation. When the flocs are broken apart, no unadsorbed flocculant is available and reflocculation cannot occur. They also found that an agitation-degraded floc can be restored to its original condition by the addition of about one tenth

the original amount of reagent.

Healy[17], in a fairly recent investigation using a quartz suspension and Dow Separan as flocculant, studied the effects of agitation on flocculation. For agitation he used a 4-blade stirrer. To measure different degrees of agitation, he used the settings on the rheostat of the stirrer motor. He found that the greater the inital polymer concentration, the more resistant the flocs will be to breaking up. For the optimum Separan concentration found (0. 85 lbs/ton solids), no floc breakup was observed until the pre-agitation was more than eight times the standard value, whereas for low Separan additions (0. 15 lbs/ton solids) significant re-dispersion occurred at twice the standard pre-agitation. His results are summarized as follows:

(1) As intensity of agitation increases, the average floc size decreases and the amount of polymer adsorbed decreases.

(2) Separan decreases the zeta potential of the silica.

(3) With increasing time of agitation at a fixed intensity, the amount of Separan adsorbed doesn't change, but the floc size decreases.

(4) The shear resistance of the flocs increases as the polymer concentration increases.

His explanation for the results was that the more intense the agitation, the more difficult it is for the polymer to adsorb a critical number of active groups onto the solid and remain attached; that is, as the intensity increases, the amount of polymer adsorbed decreases. The time of agitation, on the other hand, doesn't change the amount of polymer adsorbed, but it does break up the flocs. Considering the floc as solid particles bridged

by polymer chains, one can visualize random restricted movement of the units of the floc taking place. During this motion, the bridging segments of the polymer are reduced in length and number by adsorption on adjacent or individual particles, and the particles become less resistant to shear. At low surface coverage (low polymer addition), adsorption of extended segments is more rapidly accomplished than at high surface coverage. Thus a longer adsorption time at any fixed intensity of agitation is required at high concentrations of polymer, since the probability of an extended segment finding free surface onto which it can adsorb is less than at low surface coverage.

7. Effects of Flocculation on Hydrocyclone Operation

Except for a few passing remarks, the literature is devoid of any information on the effects of flocculation on hydrocyclone operation.

Weems[18], in discussing the advantages of a hydrocyclone for desliming pulps, said the following:

> "The high shearing stresses in the hydrocyclone tend to break up and prevent the reformation of any flocs that exist in the pulp. This feature enables classification in the cyclone free from the undesirable effects of flocculation, even without dilution or the addition of chemical dispersing agents. This makes the cyclone especially attractive for fine separation with pulps that are naturally flocculent".

Weems, however, does not refer to any specific tests made to verify this statement. The statement seems to be made only as a natural assumption in the context of his paper.

Kelsall in his 1954 paper says the following:

> "Hydraulic cyclones are simple and inexpensive in construction, with no moving parts and have extremely high capacities (200 - 400 g. p. m. per sq. ft. of area) but their application as thickeners is limited, because flocs are broken up and prevented from reforming by the high shear forces".

Kelsall also did not investigate this aspect but probably based this conclusion on the statement made earlier by Weems.

Bradley in his recent book[19] states the following:

> "Flocculation is rarely of value in cyclone operation where floccs present in the feed are broken by shear in the rotating liquid such that the settling velocity reverts to that for the basic particles".

All the above statements seem to have stemmed from Weems' discussion in which only electrolytic flocculation was considered, since synthetic polymer flocculants had not yet been discovered. The forces holding the particles together in a floc formed by electrolytes is relatively weak when compared to the hydrogen bonds used by polymer flocculants. Thus the above statements are not necessarily valid for polymer type of flocculation.

EXPERIMENTAL

A. Equipment

1. Hydrocyclone

For the test work a 1.25-inch diameter hydrocyclone was used. This hydrocyclone was designed by Lilge in accordance with the concepts propounded in his paper[1]. This size was selected for the following reasons:

(1) The shear forces present in a small cyclone are greater than those in a larger one. If flocs could be formed which would resist the shearing action in a small cone, it would prove that they would remain intact in larger sized cones.

(2) A small hydrocyclone has a low throughput capacity which makes it more desirable for laboratory work.

The hydrocyclone used was constructed with replaceable inlet, overflow and underflow orifices as shown in Figure 2. For this work an inlet orifice diameter of 1/4 inch was used throughout. The overflow and underflow outlet orifices were 1/4 and 3/16-inch diameter respectively, giving a Cone Ratio of 0.75.

The flowrate through the hydrocyclone was controlled by feed pressure. The pressure was measured through a pressure tap located on the inlet line located 28 pipe diameters upstream from the hydrocyclone. A diaphram oil seal was on the pressure gauge to prevent solids from lodging in the pressure-sensing mechanism. After several tests it was found that the gauge wasn't reliable enough and a 6-foot mercury manometer was installed on the line to supplement the gauge. To prevent

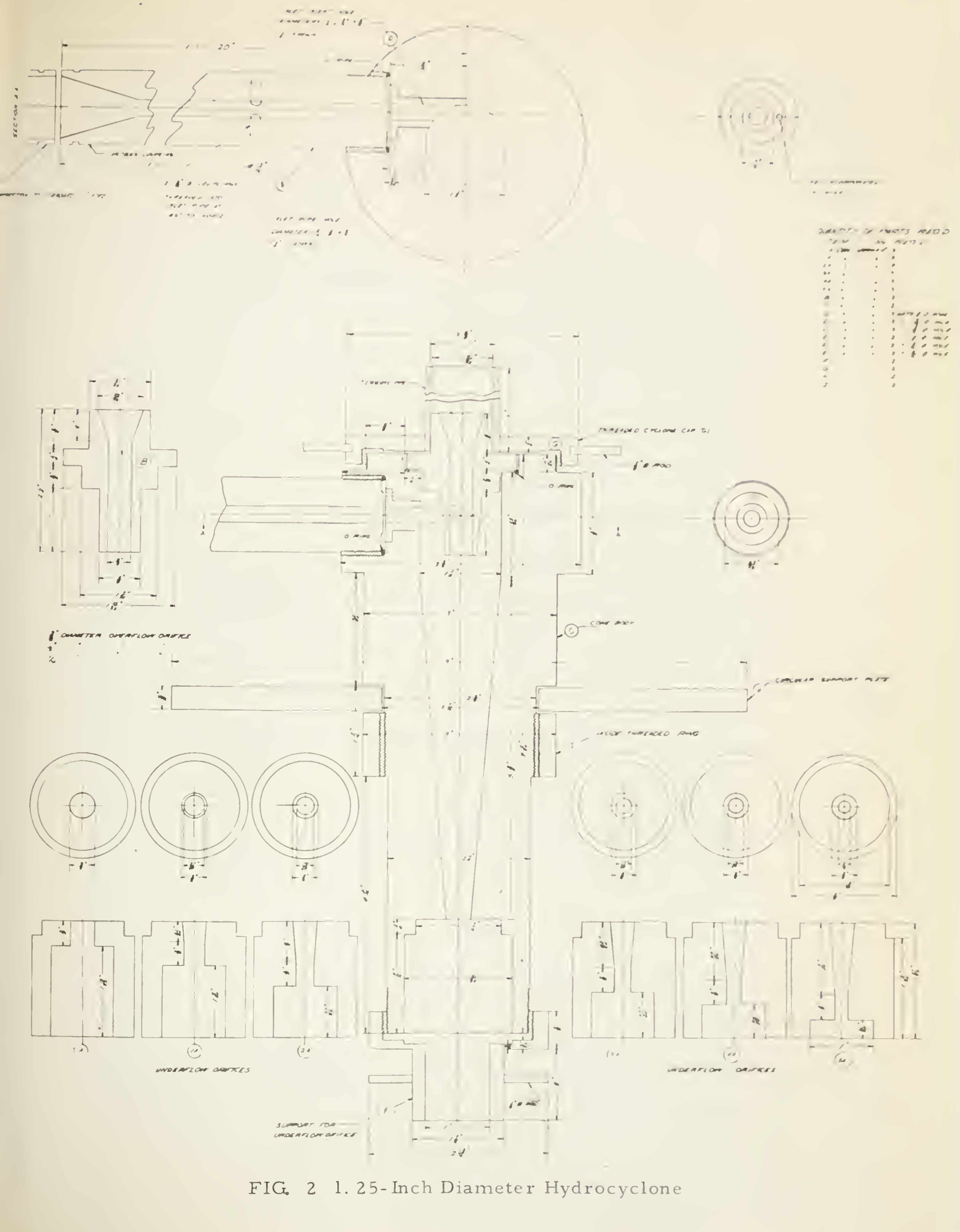


FIG. 2 1.25-Inch Diameter Hydrocyclone

solids from backing up through the interconnecting line it was continually purged with a very small flow (about 1 - 2 litres/hr) of clean water. This feature operated very well and prevented solids from contaminating the mercury.

2. Slurry Feeding Equipment

Originally it was planned that the pulp would be flocculated in a feed tank and then passed through the hydrocyclone. The feeding equipment was designed on this basis. It was evident that no pump or high shear devices could be used on the flocculated material before it entered the hydrocyclone without affecting the results. To avoid using a pump, which might break up the flocs, a system was designed whereby air pressure would force a test batch of slurry through the cone. A pressure feed tank, large enough for about 7 minutes running time, was designed and built. This tank is shown in Figures 3 and 4. The tank was registered and tested in compliance with the Alberta Department of Labour code for non-fired pressure vessels. A design pressure of 100 psi was used.

The tank was constructed from a 16-inch standard pipe with a 45° conical section welded on the bottom. A standard 100-pound, 16-inch blind flange served as cover for the tank. To facilitate entry to the tank, a 6-inch threaded nipple was provided in the blind flange cover. A quick-coupling adapter and cap was then purchased and mounted on the nipple. This served as an inspection port for the tank which could be removed quickly, yet providing a leak-proof and safe connection. This feature operated very well and completely eliminated the need for removing the large blind flange cover. Other fittings for the air inlet line, pressure

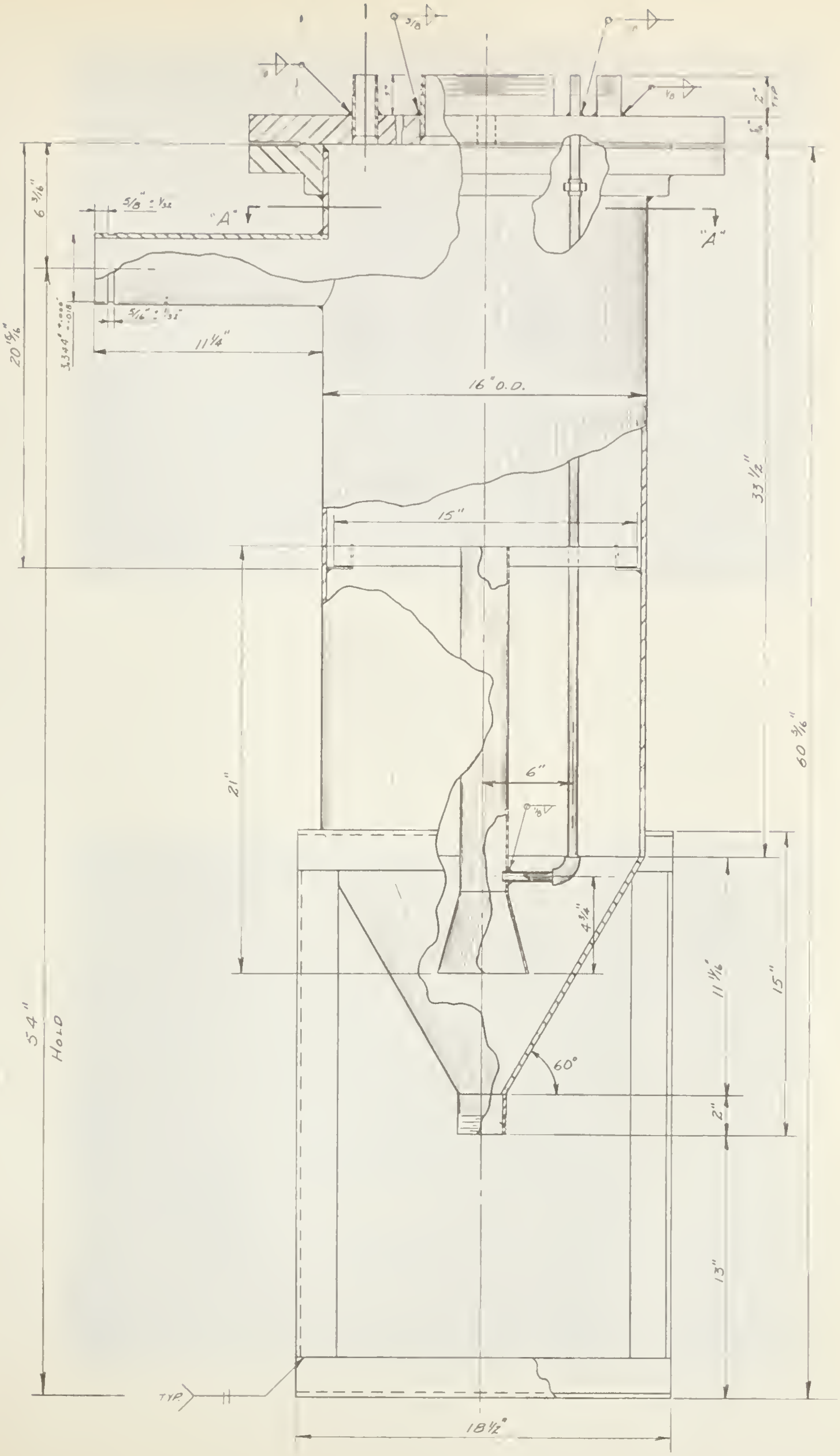


FIGURE 3. SLURRY PRESSURE FEED TANK DESIGN

FIG. 4 - SLURRY PRESSURE FEED TANK

FIG. 5 - FLOCCULANT INJECTION TANK AND RELATED EQUIPMENT

release valve, safety relief valve and pressure gauge were also provided in the tank cover.

To prevent material in the tank from settling, an air lift mixer was installed inside the pressure tank as can be seen in Figure 3. The mixer consisted of a 2-inch pipe with a flared inlet. This pipe was suspended in the tank so that air injected in the pipe would lift the slurry from the bottom to the upper portion of the tank, thus keeping the slurry at a uniform pulp density. The mixer was modified after initial tests by drilling holes in the wall of the pipe so that circulation would be maintained as the liquid level dropped below the top of the pipe. This device provided adequate mixing for slurries with low settling velocities. However for slurries that contained solids with high settling rates, a more vigorous mixing action was required.

To prepare and hold slurries, an existing open-topped tank was incorporated into the system. This tank was located above the pressure feed tank so that the feed tank could be filled by gravity via an interconnecting 3-inch pipeline. A 1/2 H. P. Greey "Lightnin" mixer was mounted in the upper tank to provide mixing action during slurry preparation.

3. Flocculant Injection System

After carrying out preliminary settling tests on flocculated pulps, it became evident that any attempt to flocculate the pulp in the feed tank would be unsuccessful for two reasons:

(1) the settling rate of a flocculated pulp is so high that a constant pulp density could not be maintained without the use of high shear mixing devices.

(2) adsorption of the flocculants by the solids is so rapid that it would be impossible to disperse the flocculant uniformly throughout the pulp.

For the above reasons it was decided that the flocculant would have to be fed into the feed line to the hydrocyclone. The flow in the cone inlet line, being highly turbulent, would provide the necessary mixing for adequate dispersion of the flocculant.

A flocculant injection tank was built, patterned after the design used for the larger slurry feed tank. A photograph of the tank and related equipment is shown as Figure 5. To provide the pressure, a compressed nitrogen cylinder equipped with a pressure regulator was connected to the tank.

To meter the flow of flocculant to the feed line, a rotameter was selected as being the best-suited type of flow meter. For the job, a 3/4 inch Brook's Model 1112A "O" Ring rotameter was purchased. By using different floats in the instrument, flow measurement, accurate to within 2 percent over a wide range of flow rates, was possible.

A swing check valve was installed on the flocculant injection line. This one-way valve ensured that no slurry could back up from the hydrocyclone feed line and contaminate the flocculant and block the injection lines.

For tests in which the flocculant was to be introduced directly into the hydrocyclone, and at various points in the feed line upstream from the cone, a special injecting device was built. A 45^{o} Y-bend was attached to the feed line about 2 feet upstream from the cyclone. A pressure seal was built using a packing and a gland and a 1/16 inch O. D. tube was inserted through the seal into the feed line as may be seen in Figure 8.

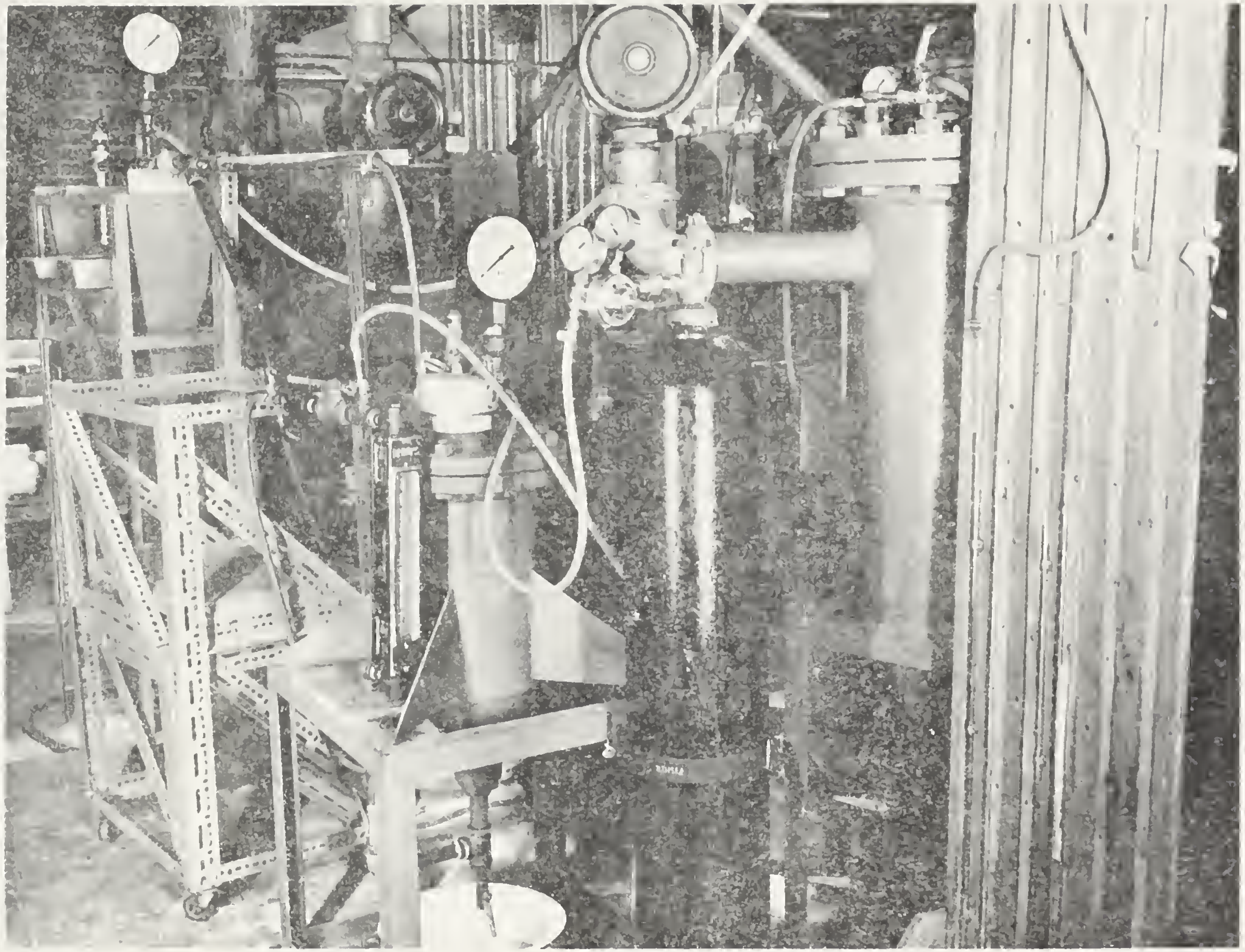


FIG. 6 - OVERALL VIEW OF TEST EQUIPMENT

The injection tube was as small as possible and yet large enough to be able to pass the desired flow of flocculant. The tube occupied only 6 percent of the inlet area and so did not appreciably upset the slurry flow. The injection tube was then slid into the inlet line to the desired point, and by loosening the gland could be readjusted to a new position during the course of a test.

4. Slurry Return System

When operating with unflocculated material, the slurry is not physically changed in passage through the hydrocyclone. Provision was therefore made to recirculate the unflocculated hydrocyclone discharge to the slurry feed tank. This had the advantage of being able to carry out two tests on the same material, first in its natural state and then in the flocculated state.

To return the material to the slurry mixing tank, an existing Denver sand pump was incorporated into the system. When operating with flocculated material, the cyclone discharge was routed directly to the sewer so that the slurry tanks were never contaminated with flocculant.

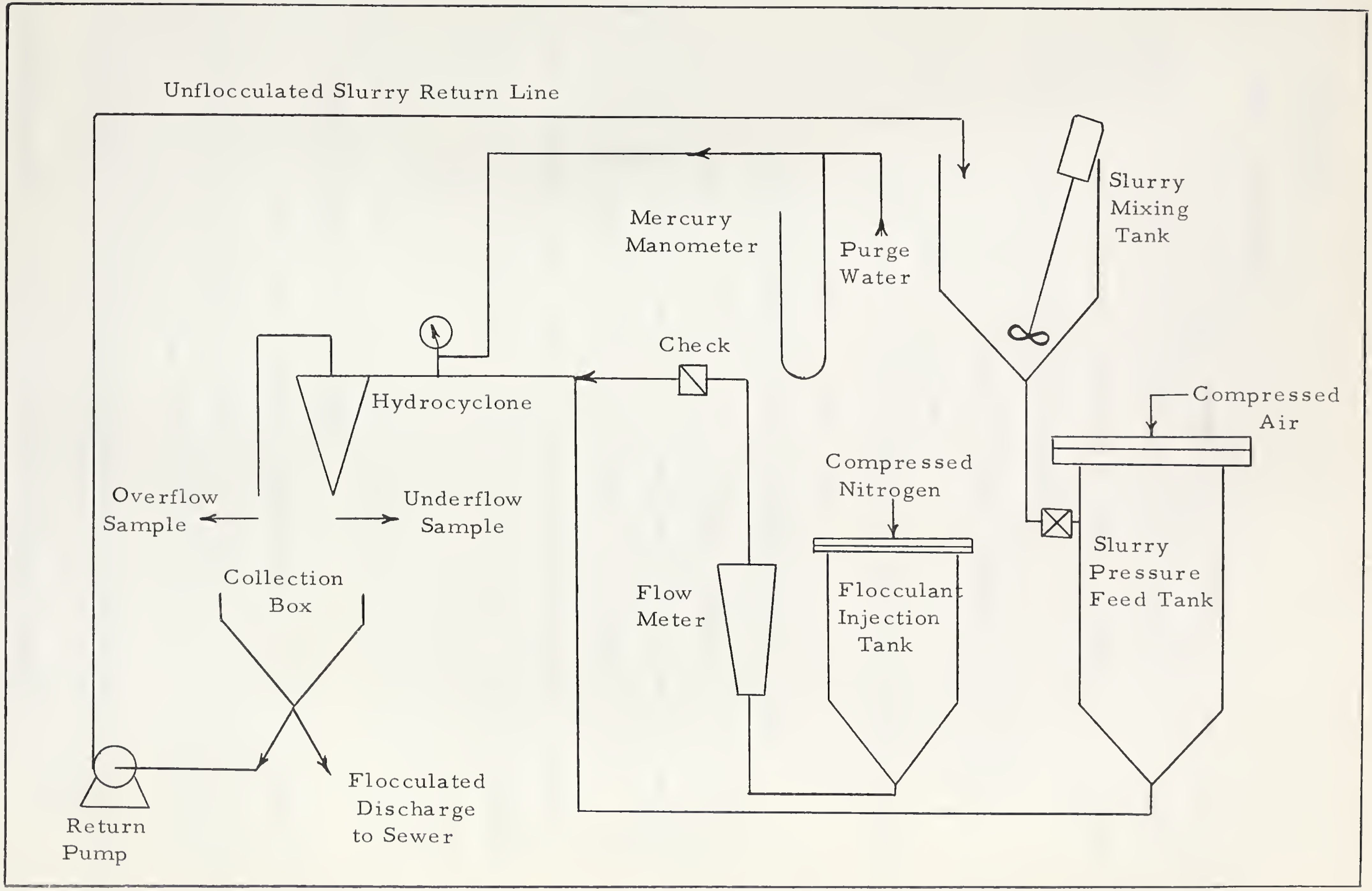


FIG. 7 SCHEMATIC DIAGRAM SHOWING ARRANGEMENT OF EQUIPMENT

B. Procedure

1. Slurry Preparation

The bulk of the experimental work was carried out on a 5 percent slurry of commercially available kaolin clay* and tap water. The clay is mined from sedimentary deposits in central Georgia. The manufacturer describes the processing as follows:

1. Crude clay is dispersed into an aqueous slurry form.
2. The slurry is degritted.
3. The slurry is centrifugally fractionated into various products saving different particle size distributions.
4. The fractionated products are bleached and dried.

The manufacturer lists the average particle size as 4.8 microns equivalent spherical diameter. A size analyses was carried out by the density sedimentation hydrometer method as described in Orr[20]. The size distribution curve obtained from the tests is shown as Figure 5. The average particle size was measured as being 5.7 microns Stokesian diameter. With regard to particle shape, the manufacturer describes the material as being thin, flat laminated plates.

2. Flocculant Solution Preparation

For all the tests a commercially available, non-ionic polyacrylamide flocculating agent** was used. Preliminary settling tests shows that this flocculant was one of the best for the clay slurry. Results of the

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*The product is sold under the brand name of ASP 400 and is produced by the Minerals & Chemicals Philipp Corporation of New Jersey.

** Separan MGL manufactured by Dow Chemical Company.

settling tests are found in Appendix I.

The flocculant was dissolved in water. Because it is not readily soluble in water, several hours of continuous stirring is required to dissolve the material. To provide adequate dispersion of the flocculant, dilute solutions were always used.

To avoid possible breakdown of the flocculant, solutions were only kept for two weeks at a maximum. To allow the flocculant molecular chains to unravel fully, solutions were never used until they were more than one day old.

3. Thickening Measurements

The objective of the tests was to determine what effects the flocculants would have on the thickening capabilities of the hydrocyclone. The testwork consisted of a series of measurements with, and without, the use of flocculants. Conditions such as, amount of flocculant used, point of addition, and hydrocyclone flowrate, were varied from test to test in an attempt to optimize the thickening.

The flowrate of the slurry feed was controlled by the inlet pressure measured on the inlet line to the cone. Air pressure to the feed tank was adjusted to obtain the desired feed pressure. When the desired flowrate was established, the overflow and underflow streams were simultaneously sampled, as shown in Figure 8. The duration of each sample cut was timed by a hand-operated stopwatch.

For the tests not using a flocculant, the slurry was returned to

the slurry mixing tank. The slurry was then again routed through the hydrocyclone with flocculant injected into the feed line. The addition of the flocculant solution was controlled by adjusting the nitrogen pressure to the flocculant injection tank to obtain the rotameter reading corresponding to the desired flocculant flowrate. The rotameter was calibrated prior to each test run. Once all the flowrates were set, samples of the cyclone outlets were again taken in the same manner as before.

Each slurry sample was weighed and then filtered. The filtered solids were then dried and weighed. The dry and wet weights provided the data from which thickening efficiency could be calculated.

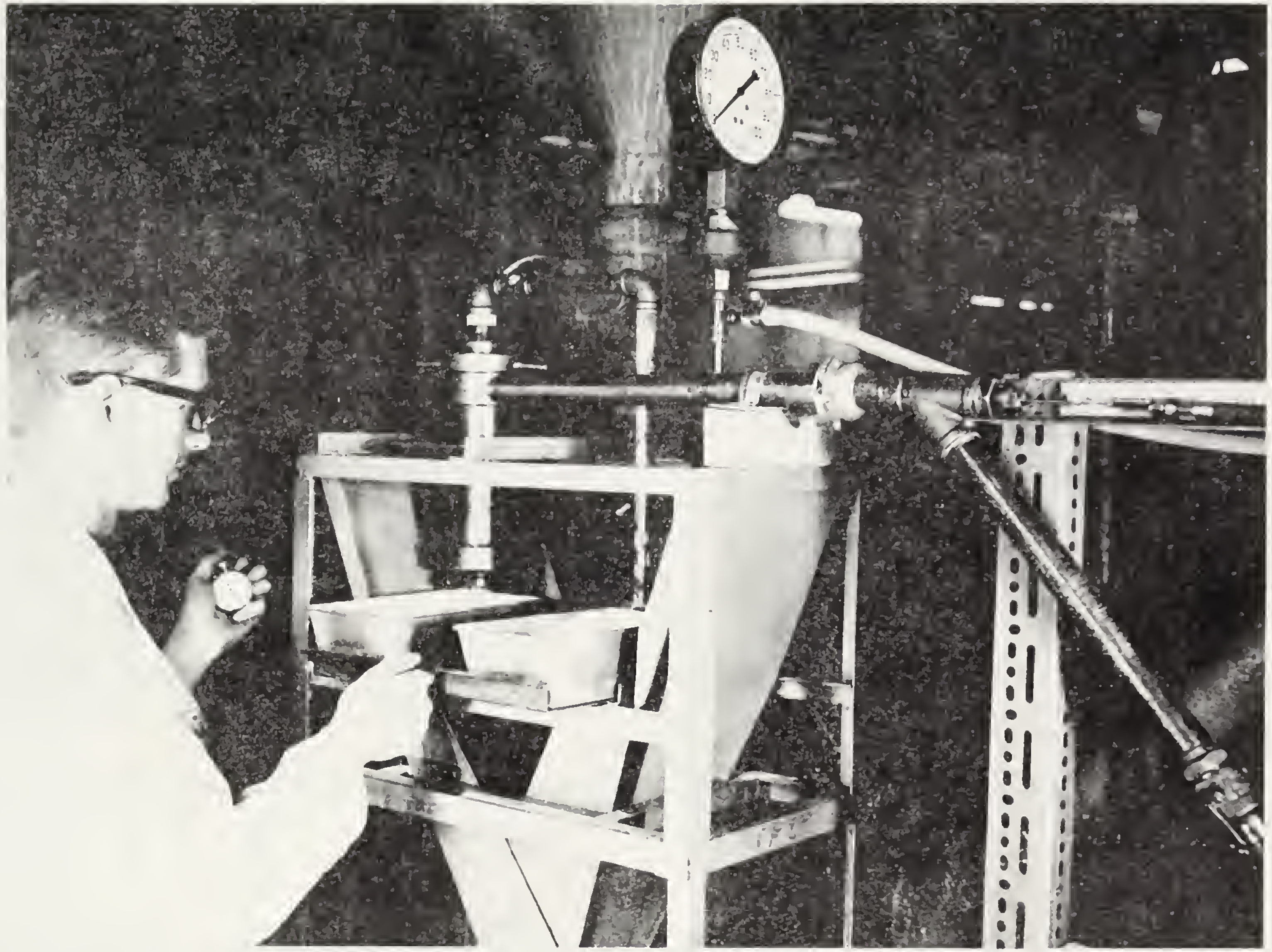

FIG. 8 - SHOWING METHOD OF SAMPLING HYDROCYCLONE DISCHARGE

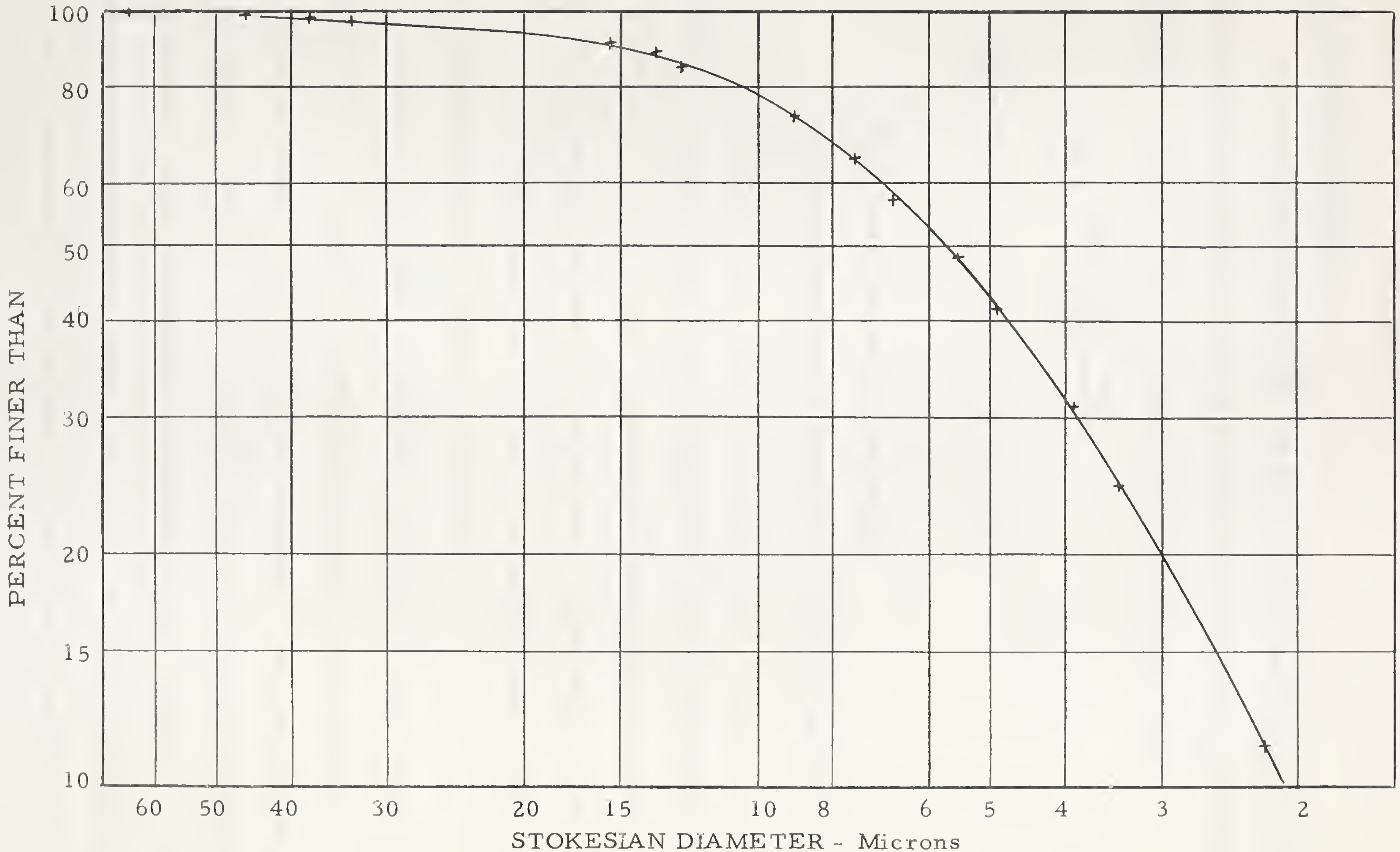

FIG. 9 PARTICLE SIZE DISTRIBUTION OF KAOLIN

RESULTS

1. Thickening Efficiency

As a measure of the degree of solid-liquid separation produced by the hydrocyclone, all the results are represented in terms of thickening efficiency. This efficiency is defined by the following equation:

$$E_t = \frac{100\,(x\,W_f - W_o)}{x\,W_f}$$

where E_t = percent thickening efficiency

x = volume fraction to overflow

W_f = mass flowrate of feed solids

W_o = mass flowrate of solids discharged through the overflow

As seen by the formula, at 100 percent efficiency no solids are in the overflow. At zero efficiency no concentration of solids takes place, hence the solids would be split in exactly the same proportions as the volumetric flow split between the two outlets. Thickening efficiency is, therefore, the percentage reduction of solids concentration in the overflow stream compared to the feed concentration.

It should be pointed out that this thickening efficiency term is not an all inclusive formula for evaluating thickening, since no term for the amount of liquid in the underflow is included. From the formula it is seen that as $x \rightarrow 0$, $E_t \rightarrow 100\%$. However from a practicle standpoint, low values of x would normally be considered as poor thickening, since the underflow would contain most of the liquid. Therefore the efficiency term is only meaningful when related to a particular Cone Ratio. For all

the tests a Cone Ratio of 0. 75 was used. Since x = fn (Cone Ratio), x also remained relatively constant at 0. 63 for all the work.

2. Effects of Flowrate and Flocculation on Thickening Efficiency

Figure 10 graphically represents the effects of polymer flocculation on thickening efficiency at various flowrates. The unflocculated and flocculated tests were carried out on the same batch of slurry. The data from which the curves are plotted are shown in Table I, Appendix II. An attempt was made to keep the flocculant loading* constant at 0. 40 lbs/ton. The actual flocculant to solids ratio was back-calculated and is shown in Part B of Table I. The flocculant loading varied from 0. 37 to 0. 51 lb/ton during the test. It is believed that this variation partially accounts for the scattered results in the test using the flocculant. However, the results clearly show that thickening efficiency is increased by the addition of a flocculant.

3. Flocculant Loading and Injection Point

A series of tests was carried out to determine the relationship between flocculant loading and the point where the flocculant is introduced in the feed line. Graphs of thickening efficiency verses flocculant loading for injection at four different points in the feed line are shown in Figures 12 and 13. The curves are plotted from the results shown in Table II. The position of the points is illustrated in Fugure 11. These curves show that thickening efficiency is greater at a lower flocculant loading, when the reagent is added near the hydrocyclone.

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*Flocculant loading is defined as being the weight of flocculant added per unit weight of solids contained in the slurry.

A second series of tests was carried out to study in more detail the effects of introducing the flocculant at various points near the cone. In these tests the flocculant addition rate was held constant and the point of injection varied during each test. The results are represented graphically in Figures 14 and 15, and in tabular form in Table III. These results show that the thickening efficiency is only sensitive to changes in distance at lower flocculant loadings.

4. Multiple Point Additions

Tests were carried out to determine whether or not the efficiency could be increased by adding flocculant at more than one point in the inlet line. The results are shown in Table IV. Part A of Table IV shows the effects of increasing the amount of flocculant added farther away from the cone, keeping the total amount constant at what was previously determined as being the optimum. The results show that as more flocculant is added farther away from the cone, the efficiency tends to decrease.

In the second test shown in Part B of the same table, the amount of flocculant added was doubled. These results indicate that at above normal flocculant loadings, the efficiency is sharply reduced if a little flocculant is added farther upstream from the cone.

5. Effects of a Dispersant

Because the kaolin slurry was naturally flocculent, it was decided to see if this type of flocculation had any effect on the separation of solids in the hydrocyclone. A test was carried out on a batch of the slurry in its natural state and then in the dispersed state. The results are shown in

Table V. The results show that the addition of a dispersing agent produces no change in the operation of a hydrocyclone. This observation verifies the statement made by Weems[18] in his discussion on the usefulness of the hydrocyclone as a classifier.

6. Thickening of a Silica Slurry

One test was carried out on a silica slurry to verify the results obtained with the clay. These results are shown in Table VI. Because the material was much coarser (average size 25 microns) than the kaolin, the thickening efficiency was much greater without the use of flocculants. The results, however, still show a marked increase in thickening efficiency by the addition of flocculant.

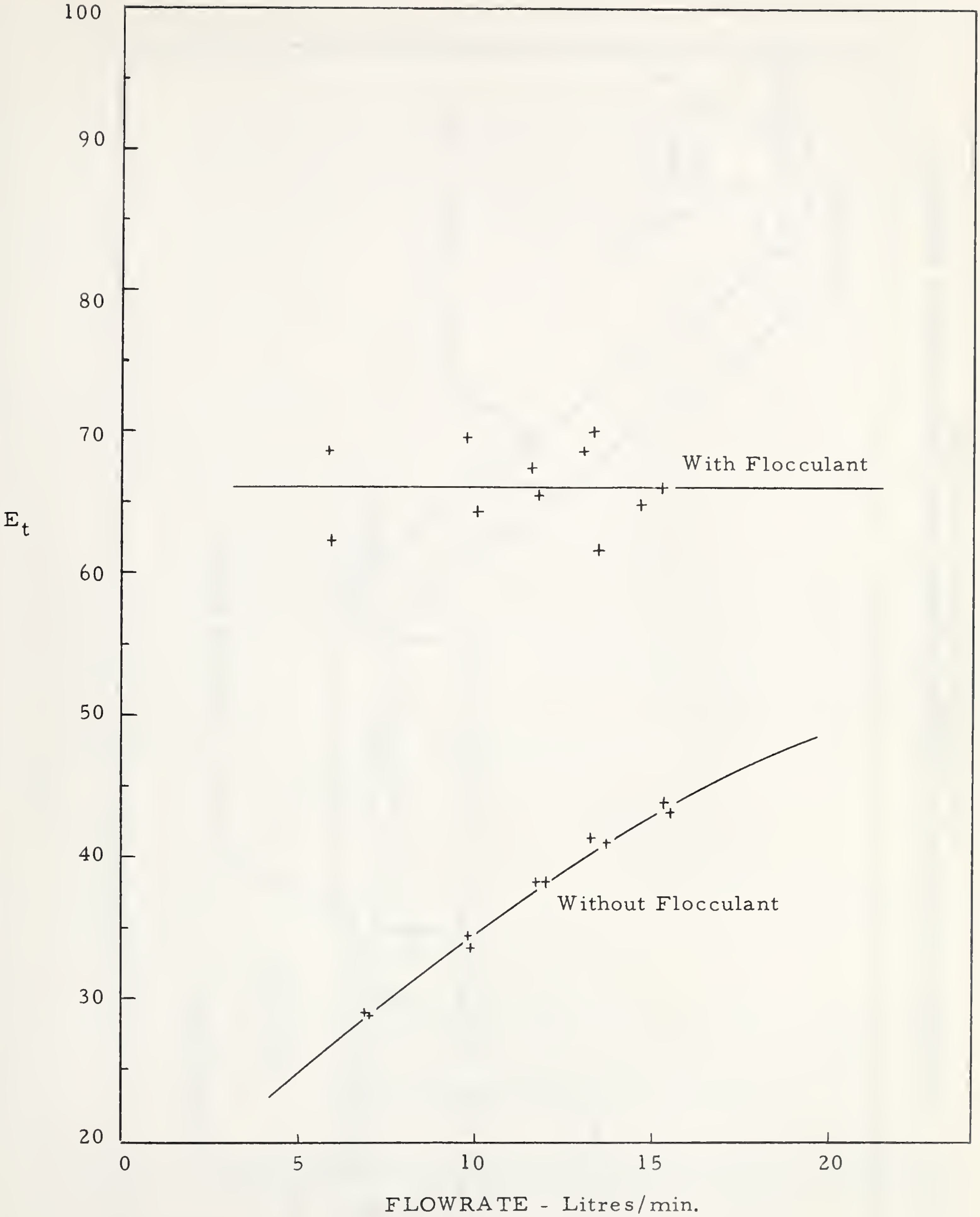


FIG. 10 THICKENING EFFICIENCY VS. FLOWRATE FOR A KAOLIN SLURRY WITH AND WITHOUT FLOCCULANT

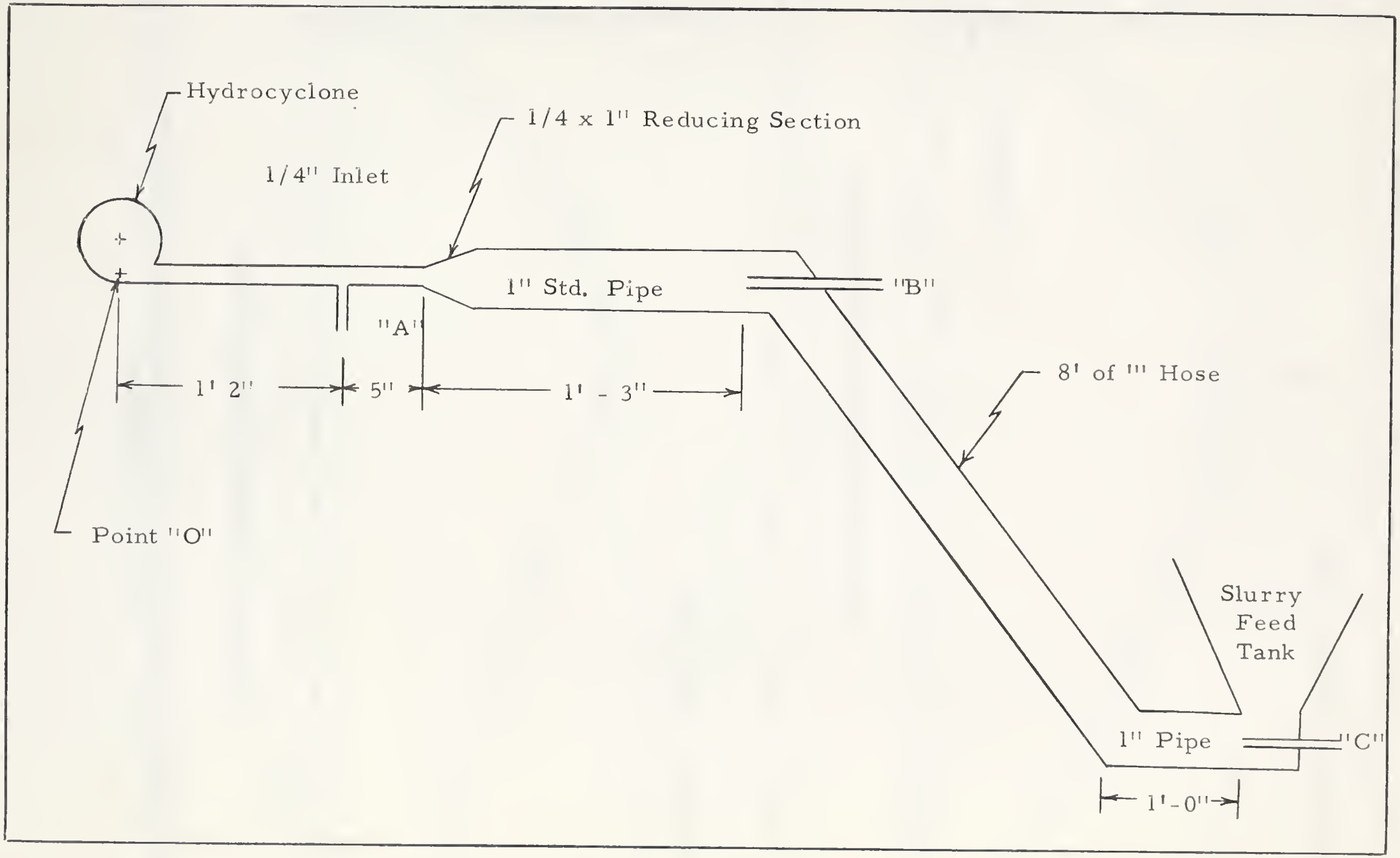


FIG. 11 SCHEMATIC DIAGRAM OF HYDROCYCLONE FEED ARRANGEMENT SHOWING FLOCCULANT INJECTION POINTS

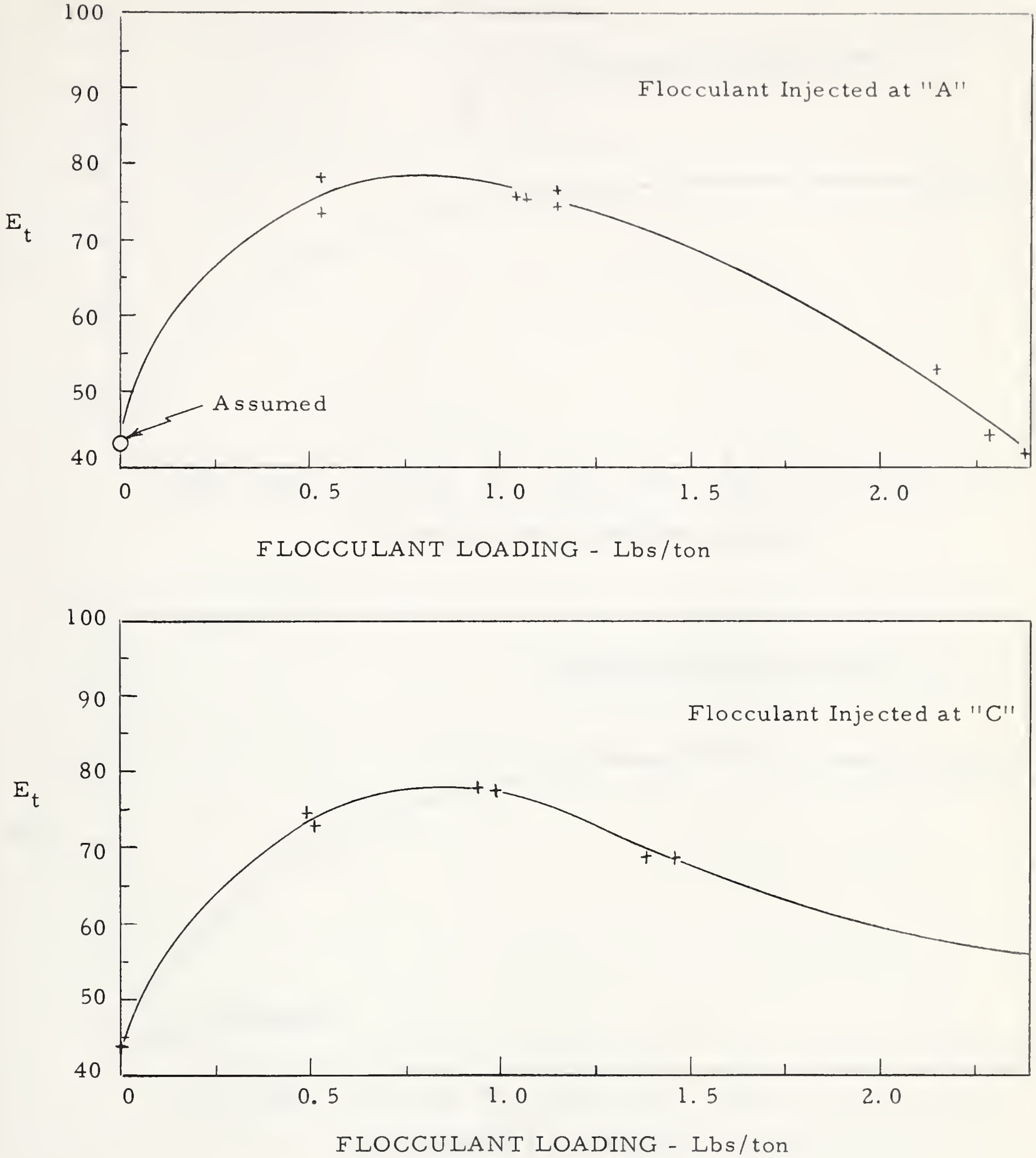


FIG. 12 THICKENING EFFICIENCY VS. FLOCCULANT LOADING AT POINTS "A" & "C"

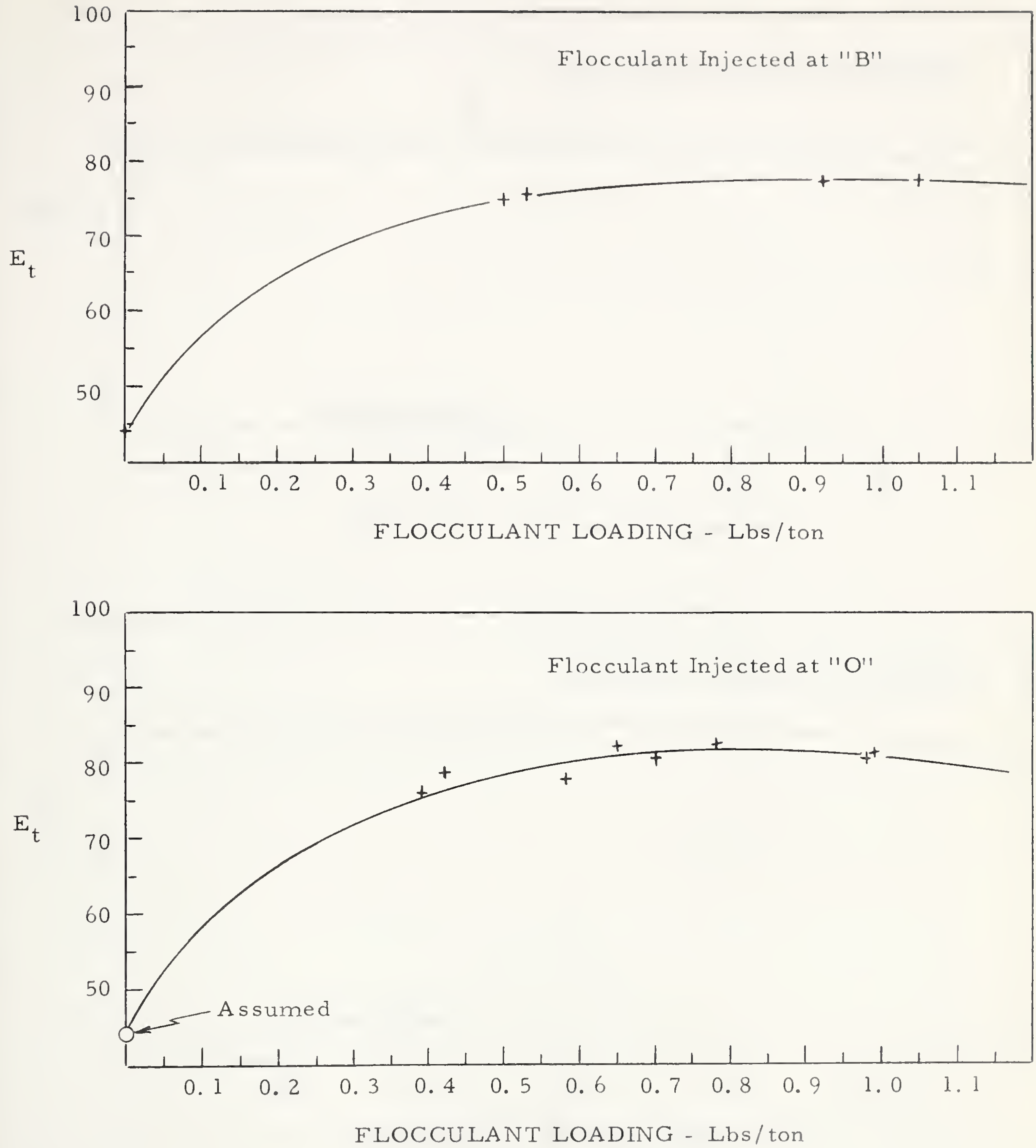
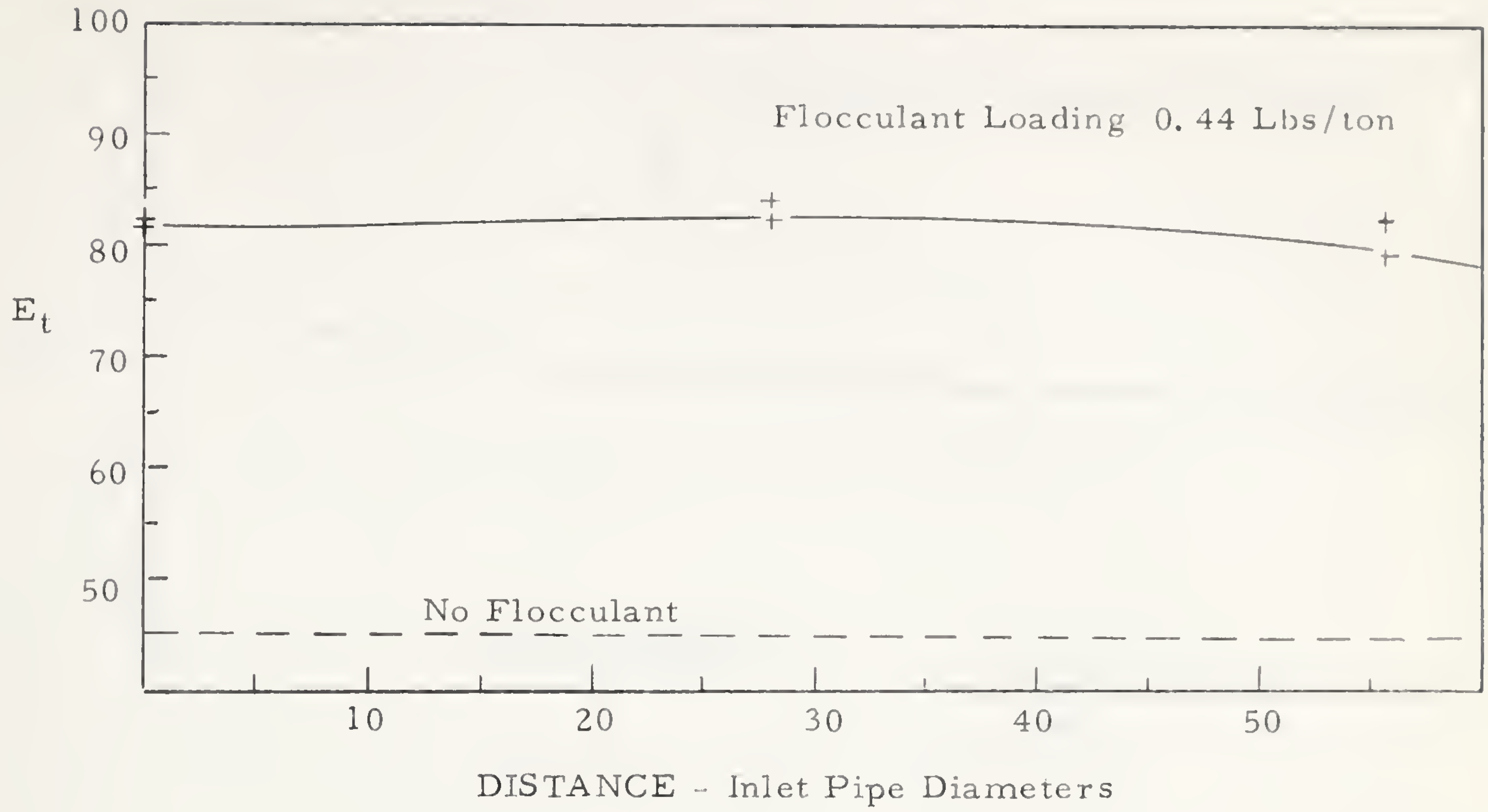


FIG. 13 THICKENING EFFICIENCY VS. FLOCCULANT LOADING AT POINTS "B" & "O"



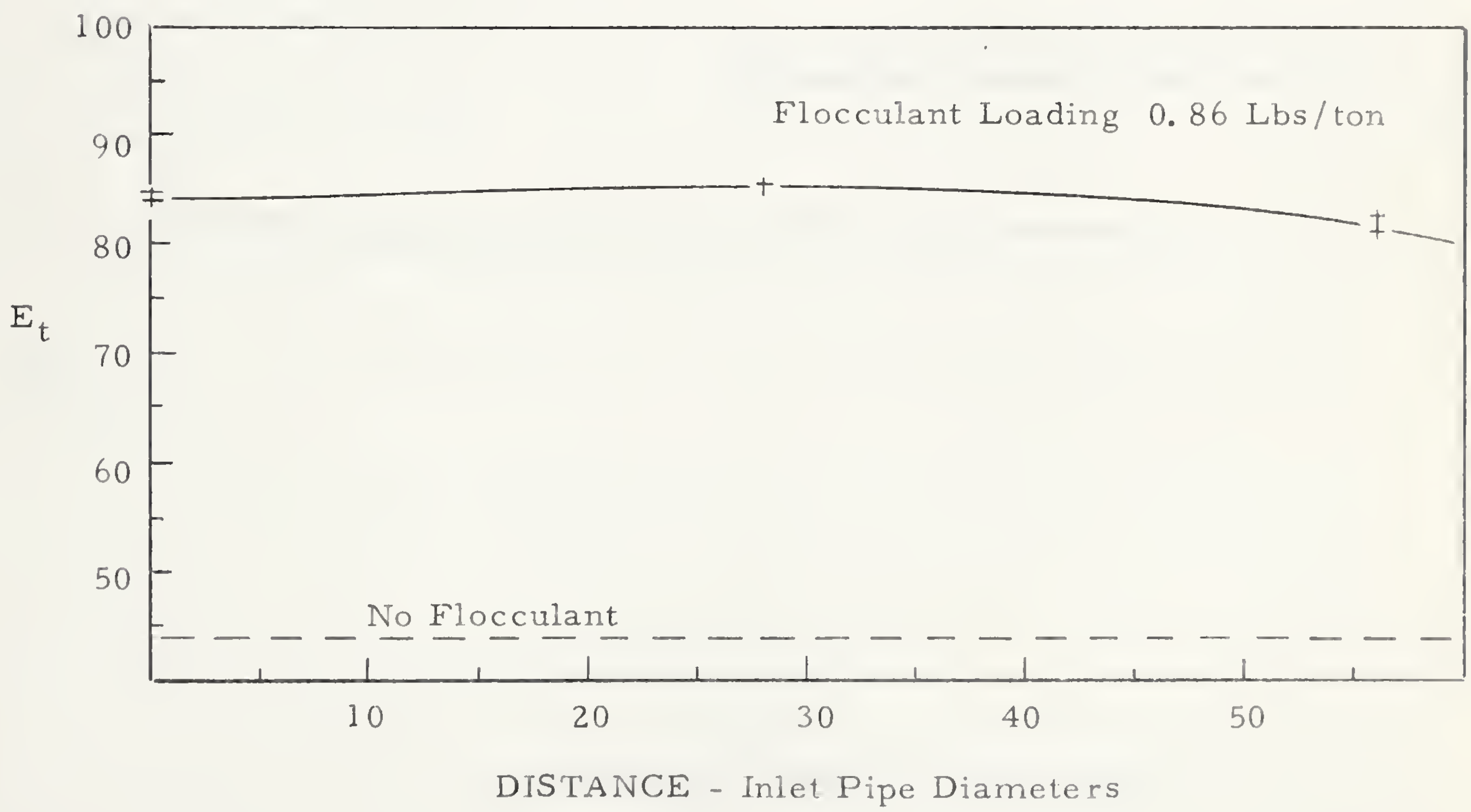
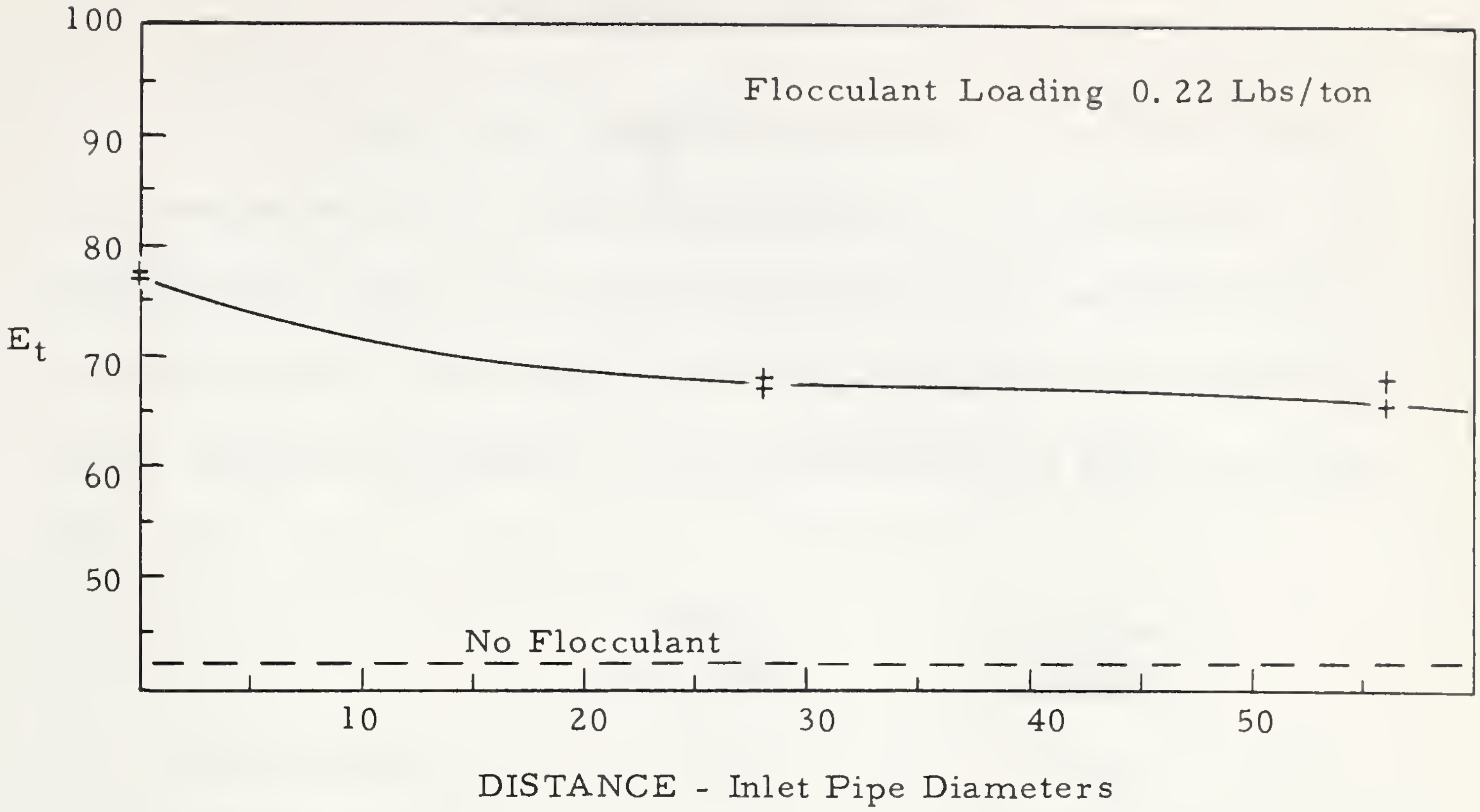


FIG. 14 THICKENING EFFICIENCY VS. DISTANCE BETWEEN HYDROCYCLONE AND FLOCCULANT INJECTION POINT



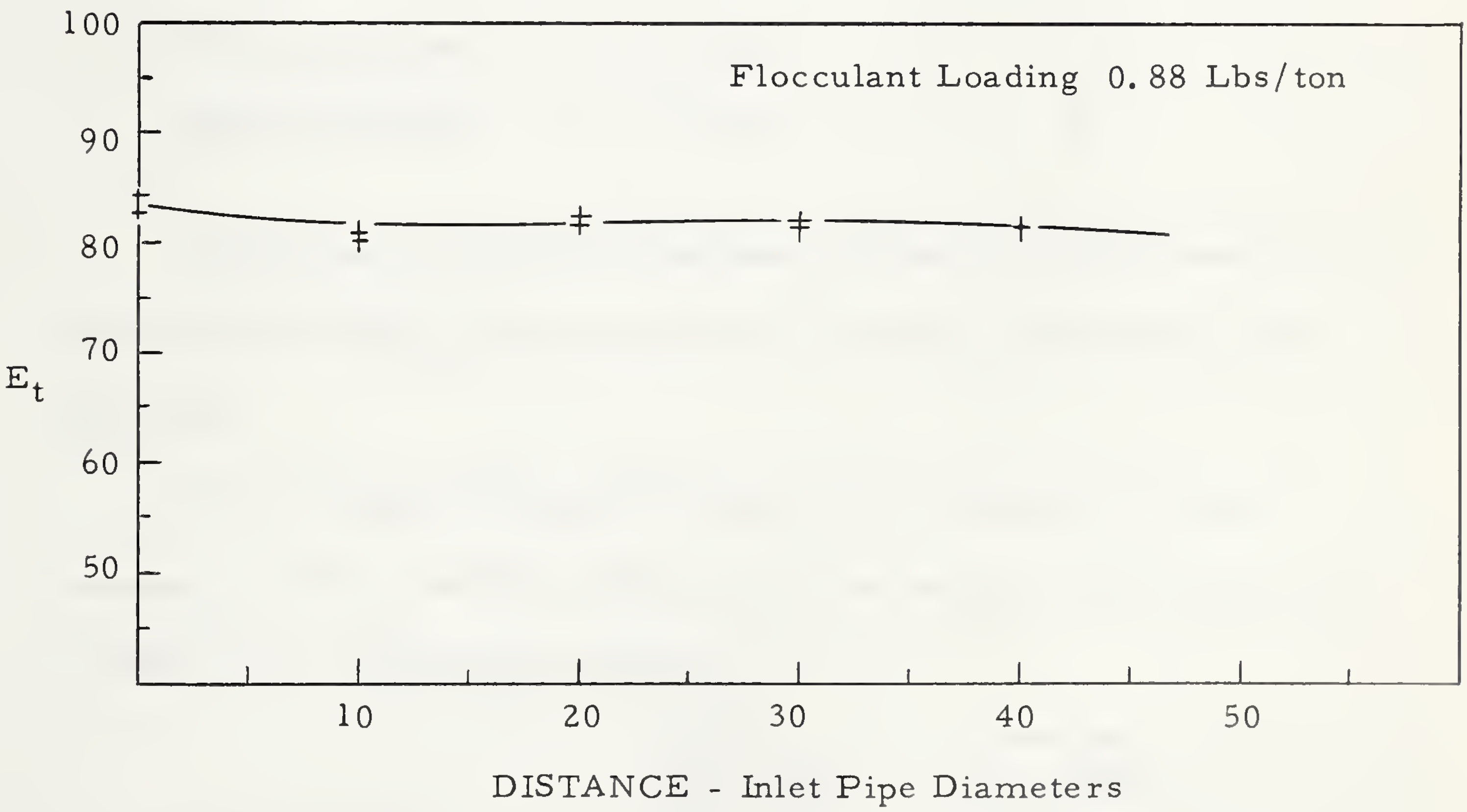


FIG. 15 THICKENING EFFICIENCY VS. DISTANCE BETWEEN HYDROCYCLONE AND FLOCCULANT INJECTION POINT

DISCUSSION OF RESULTS

The results clearly show that the addition of a polymer type of flocculant improves the thickening capabilities of a hydrocyclone. To illustrate the reduction in solids concentration in the overflow stream through the use of a flocculant, the first four results in Part B of Table III are shown as an example. The results in terms of solids concentrations are:

	Feed gpl solids	Overflow gpl solids
No flocculant	55.0	30.6
No flocculant	51.0	29.5
With flocculant	54.8	8.8
With flocculant	53.6	8.2

In the above example the presence of the flocculant reduced the concentration of the overflow solids by 72 percent of that without the flocculant.

For a coarser slurry the effects of the flocculant are also pronounced. The first five results of the test using a silica pulp shown in Table VI are presented as follows:

	Feed gpl solids	Overflow gpl solids
No flocculant	53.7	10.8
No flocculant	54.2	10.7
No flocculant	54.2	10.9
With flocculant	51.9	5.3
With flocculant	54.1	5.2

In this test, the flocculant resulted in a 50 percent reduction in solids concentration of the overflow.

The reduction in solids to the overflow is due to the formation of flocs which have a higher settling rate than the individual particles. The hydrocyclone therefore separates fluid from flocs rather than fluid from individual solid particles. The results shown in Figure 10 also support this conclusion. As the flow rate is varied the D_{50} size is varied as predicted from hydrocyclone theory. It can be shown from Formula (4) that $D_{50} \propto Q^{-0.5}$. Consequently, as the flowrate increases, the D_{50} size will decrease. The effect of a D_{50} size decrease will normally be to route more solids to underflow and less to overflow which would be reflected as an increase in thickening efficiency. This increase is shown in the curve for the unflocculated material in Figure 10. If, however, all the particles in the pulp are several times greater than the D_{50} size, a change in the D_{50} size would not be reflected as a change of thickening efficiency. Thus in the test using the flocculant it can be assumed that the flocs had an equivalent settling size much greater than the D_{50} size, such that the change in D_{50} size caused by the change in flowrate produced no significant change in thickening efficiency, as shown by the "With Flocculant" curve in Figure 10.

In the tests carried out some solids still appeared in the overflow with the use of flocculants. The reason why a perfect separation cannot be made is assumed to be mainly caused by the liquid shearing forces in the hydrocyclone. The shearing forces tend to tear the flocs apart and,

once torn apart they would not join up again, since at normal flocculant loadings no polymer molecules are available in solution for reflocculation to occur. It is this shear that is generally assumed to be the reason why flocculation resulting from the presence of electrolytes has no effect on cyclone operation, as is verified by the tests shown in Table V. The shearing forces in the hydrocyclone would for the most part be due to the tangential velocity gradient. Assuming the relationship $V_t R^{0.8} = K$ (a constant), the shear rate would be:

$$S = \frac{dV_t}{dR} - \frac{V_t}{R} = -1.8\,KR^{-1.8}$$

This formula shows that the shear rate is least near the cone periphery and greatest on the envelope of maximum tangential velocity. Substituting the velocities calculated in Appendix III, the shear rate at the radius of entry is calculated at 907 sec^{-1}, and at the radius of V_t = max, the shear rate is 15,300 sec^{-1}. Accordingly, if the flocs remain concentrated near the walls of the cone they remain in the lower shear region. However as the flocs are carried downward into the conical section they are guided closer to the cone centre into the high shear region, where some flocs would be torn apart. Some of the fine particles broken away from the flocs would then be carried along to the overflow.

The optimum flocculant loading for the kaolin slurry, as seen from Figures 12 and 13, appears to be about 0.8 lbs/ton of solids. The manufacturer* lists the flocculant consumption for most settling processes as being in the range from 0.01 to 0.5 lb/ton. As would be expected, the flocculant dosage rate is higher for thickening in a hydrocyclone than

* Dow Chemical Company

gravity thickeners since the optimum flocculant: solids ratio is mainly a function of the degree of agitation imposed on the mixture[13]. The results also show that at higher-than-optimum flocculant loadings the thickening efficiency is decreased. When the amount of flocculant present is excessive, the surface of the particles becomes coated with adsorbed flocculant molecules before the interparticle collisions needed for flocculation can occur. The particles then tend to be insulated from each other by the adsorbed flocculant.

The thickening efficiency for the very high values shown in the upper curve in Figure 12 appears to drop below the efficiency with no flocculant added. It was also noted in the preliminary test work, not shown in the results, that flocculant loadings of around 5 lbs/ton produced thickening efficiencies of around 23 percent, which is well below that obtained in any tests without flocculant. The decrease must be due to the increase in viscosity resulting from unadsorbed flocculant in solution. Although no data are available for viscosities of flocculant solutions at very low concentrations, one can obtain an indication of what it might be by the results obtained at higher concentration. Dow Chemical Company lists the viscosity of 5 gpl Separan AP30 solution as being 1200 centipoise. This clearly shows that the presence of the polymers in solution increases the viscosity. It can be shown that a change in the fluid viscosity from 1.0 to about 1.9 centipoise would be needed to obtain an efficiency of 23 percent with the unflocculated kaolin pulp. A change of viscosity of this magnitude does not seem out of line with what one might expect for the fluid at these high flocculant loadings.

Figures 12 and 13 also indicate that the point of optimum thickening efficiency occurs at higher flocculant loadings when the point of injection is further upstream from the cyclone. They also show that the highest thickening efficiency was obtained when the flocculant was added at Point "O". Some floc breakdown must occur in the inlet line which increases the requirement for flocculant and results in poorer thickening.

The curves shown in Figures 14 and 15 show that no significant change in thickening efficiency occurs at optimum flocculant loading with changes of flocculant injection position up to 50 pipe diameter upstream from the cyclone. At lower flocculant loadings the decrease in thickening efficiency as the injection point is moved upstream becomes more pronounced. This decrease is particularly evident in the curve representing one fourth of the optimum flocculant loading (0. 22 lbs/ton).

The results of the preliminary tests which were carried out to compare different types of flocculants are shown in Appendix I. These tests showed that the nonionic high molecular weight polyacrylamide flocculants give the best results. The selection of Separan MGL over Superfloc 20 was quite arbitrary and it is quite possible that the Superfloc 20 would give slightly better results. Preliminary hydrocyclone tests, not shown in the results, were carried out using Superfloc 20, and the results were about the same as those obtained with Separan. No further attempts to compare the flocculants using the cyclone were made, since the preliminary settling tests were considered adequate for the purpose of this work. As may be seen in the results, an attempt was made to duplicate the work of Wadsworth and Cutler in the use of co-precipitated

flocculants[15]. The Lytron flocculant, when used by itself, acted as a dispersing agent on the kaolin. When used together with the glue, the pulp flocculated but not nearly as well as the polyacrylamides. Co-precipitation of the polyacrylamides was also investigated. Very good results were obtained, but only at extremely high flocculant loadings for which the reagent cost would be prohibitive for most operations.

A rough indication of the time required for floc formation can be obtained from the results. The volume of the hydrocyclone used for all the tests was 70 millilitres. At a flowrate of 14 litres per minute, the average retention time of the slurry in the hydrocyclone is 0.3 seconds. In the tests carried out with the flocculant added at the mouth of the cyclone inlet, the time required for dispersion and adsorption of the flocculant to form flocs must be less than this time. The results also show that the thickening efficiency was not increased by increasing the flocculant retention time, either by decreasing the flowrate or adding the flocculant upstream from the cyclone. This indicates that the limiting time required for the flocculant to react was not reached, and consequently must be some value less than 0.3 seconds.

The D_{50} size determinations shown in Appendix III are included to illustrate the application of the hydrocyclone theory. The apparent discrepancy between the actual and calculated D_{50} sizes are probably due to one, or a combination of the following factors:

(1) The method used to calculate the radial velocity may give low results as indicated by Bradley[6]. The increase in radial velocity required

to produce the correct result would be about 6 times the value used. It is, however, highly unlikely that the value used is in error by this amount.

(2) The value of "n" used to determine the tangential velocity may be lower than the assumed value of 0.8 for the relatively small cyclone used. To increase the D_{50} size by a factor of 2.4 entirely by a change in "n" would require a change from 0.8 to 0.24. Again a change of this magnitude appears unlikely.

(3) In both cases the size was reported as the diameter of a sphere which would settle at the same rate as the actual particle. The kaolin particles are however not spherical, but plate-like in shape. This shape would not make any difference unless the particles had a different orientation in the settling tests used for size determination than they had in the hydrocyclone. In straight gravity settling in the laminar regime, the particles assume a completely random orientation[24]. In the cyclone, however, as discussed by Lilge[1], there is reason to assume that the tangential velocity gradient would tend to align the particles so that they would present their largest area normal to the radial velocity. This alignment would increase the fluid drag force which would be reflected as an increase in the stokesian D_{50} size.

Summary of Results

(1) Polyacrylamide-flocculated solids are separated in the hydrocyclone on the basis of the settling properties of the resulting flocs rather than the settling properties of the discrete particles.

(2) Flocculation by mechanisms other than the bridging action of polymer

type flocculants has no effect on hydrocyclone operation.

(3) The optimum point of addition of the flocculant appears to be in the upper portion of the hydrocyclone at the mouth of the feed inlet. Adding the flocculant more than 50 inlet pipe diameters upstream from the cyclone reduces the thickening efficiency.

(4) Flocculant additions made at more than one point in flow stream results in poorer thickening than if single point additions are made.

(5) The required flocculant dosage for hydrocyclone thickening is greater than the dosage required for gravity thickening.

(6) Increase of flocculant dosage beyond the optimum will result in poorer rather than better thickening. Additions of 3 to 4 times the optimum dosage will reduce the solids recovery to a point below that obtained without the use of a flocculant.

(7) In a turbulent flow stream the time required for polyacrylamides to flocculate solid particles is less than 0. 3 seconds.

CONCLUSIONS

The results show that hydrocyclones can be designed for thickening on the basis of the settling velocity of flocs resulting from the addition of polyacrylamide flocculants. To achieve the same degree of thickening obtained in the tests, but without the use of flocculant, would require a cyclone operating with a D_{50} size of 2 microns (estimated from Figure 9). To obtain this D_{50} size would require a cyclone with a diameter calculated* at 0.24 inches. This smaller cyclone would have a capacity of about 0.6 litres per minute. To process the slurry at the rate of 14 litres/min. obtained with the 1.25 inch cyclone, would require a bank of 23 of these smaller cyclones operating in parallel. This rough calculation clearly demonstrates the practical significance of the information obtained from this work.

Although this work was carried out with a 1.25 inch cyclone which has a relatively low capacity, it is postulated, however, that the use of flocculants would recover the fines equally as well, or even better, in larger cyclones.

Although the elimination of solids is not as perfect as could be achieved through the use of a gravity thickener with the aid of flocculants, cyclone thickening can still be applied to the many thickening operations

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* The size and throughput were determined using the relationships given by Bradley[19] for comparing geometrically similar cyclones operating at constant pressure. These relationships are:

$$D_{50} \propto D_c^{0.45}$$

$$Q \propto D_c^{1.9}$$

which can tolerate a small amount of fine solids in the overflow. In these cases the inherent advantages of the hydrocyclone over gravity thickeners can be profitably utilized. These advantages include: simplicity, which results in low initial and operating costs, small space requirements, and versatility of application. It is thus concluded that hydrocyclones when used in conjunction with flocculants have great potential in the field of thickening.

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APPENDIX I

PRELIMINARY FLOCCULANT EVALUATION

Flocculant Evaluation

Oliver in his 1963 paper[21] listed over 100 reagents which were then being marketed as flocculants. By now the list has grown as new products are introduced. Because of the formidable task of evaluating all the flocculants, only 9 were selected for testing.

The object of the evaluation was simply to find a flocculant which would form relatively stable and shear resistant flocs of the kaolin slurry. During the course of the evaluation it was found that the clay was naturally flocculent in tap water and slightly more flocculent in distilled water. The reason for the flocculation is assumed to be due to the fact that kaolin carries a positive charge on its edges and a negative charge on the face of the platelike particle as described by Van Olphen[22]. This difference in electrical charge would result in an edge to face attraction which would result in the formation of flocs. The edge charge is reversed in alkaline solutions which accounts for the decrease in flocculation in tap water which has a pH of 8.

Manufacturers Description of the Flocculants Evaluated

Dow Chemical Co. Flocculants

Separan NP 10

This flocculant is a high molecular weight synthetic polymer formed from the polymerization of acrylamide. The molecular weight is approximately 1 million.

Because of the preponderance of amide groups, polyacrylamide is essentially nonionic in solution, although a small portion of the amide

groups are usually hydrolyzed to anionic carboxyl groupings.

Separan AP30

This flocculant is a high molecular weight synthetic polymer of acrylamide containing both amide and carboxylic groupings. Separan AP30 is classified as an anionic polyelectrolyte in neutral and alkaline solutions. Under acidic conditions the ionization is repressed and the polymer assumes a nonionic character. The molecular weight of the polymer is estimated as being between 2 and 3 million.

Separan MGL

This flocculant is similar to Separan NP10 except that its molecular weight is in the 2 to 3 million range.

Separan C-90

This flocculant is similar to Separan AP30 except that the ionic character is cationic in aqueous solution.

American Cyanimid Company

Superfloc 20

This reagent is a polyacrylamide with a nonionic character which is effective in both highly acid and alkaline systems.

Rohm & Haas

Prima floc C-7

This substance is described as being a water soluble polyelectrolyte (polyamine) possessing a high cationic functionality and a very high molecular weight.

Canadian Industries Limited

Sedomax F

This flocculant is an anionic acrylic polymer.

Monsanto Chemical Company

Lytron 886

This reagent is described as partial calcium salt of a carboxyl containing high molecular weight copolomer of vinyl acetate and maleic anhydride. The substance exhibits an anionic functionality.

Canada Glue Company Limited

Standard IX Flocculating Glue

This material is described as a long chain animal glue of proteinaceous colloids derived from rawhide stock. The glue is normally cationic in nature.

Procedure

A procedure was devised for measuring the shear resistance of the flocs. The method is a combination of the techniques used by Healy[17] and Booth et al[23]. The procedure was as follows:

(1) Enough clay to form a 5 percent slurry by weight in 1.05 litres was dispersed in 600 ml. of tap water.

(2) The slurry was washed into a 5-inch diameter cylindrical container with enough water to bring the volume up to 750 ml.

(3) The slurry was then agitated using a Jumbo mixer with a 4-blade, 3.5-inch diameter impeller with 0.75 inches clearance from the bottom of the container. The speed of the mixer was set with a rheostat to turn at 600 RPM.

(4) The required amount of flocculant solution was diluted with water to bring the volume to 300 ml. The flocculant solution was then added to the edge of the vortex in 5 seconds. The slurry was agitated for 60 seconds from the beginning of the flocculant addition.

(5) The solution was poured into a graduated 1000 ml. cylinder. The solution was mixed with 3 strokes of a plunger.

(6) Timing was started as the interface between the settling pulp and the clear liquid passed the 1000 ml. mark.

(7) The time required for the pulp to settle to the 700 ml. mark, a distance of 10.5 cms., was recorded. The settling velocity in this part of the column was used because the pulp was in the free settling regime.

(8) After 4 minutes of settling, 10 ml. of solution was drawn off and the turbidity was determined. The turbidity was measured as percent transmittance of light through the sample using solids-free tap water as a calibration standard for 100 percent. The measurements were carried using a Bausch and Lomb, "Spectronic 20", colorimeter.

Settling Test Results Using 5 percent Kaolin Slurry

Flocculant Used	Flocc Loading lbs/ton	Settling Rate cm/min	Clarity-Percent Transmittance
No Flocc.	0	1.4	53
Separan NP10	.05	5.7	59
	.10	6.3	68
	.20	8.5	73
	.30	9.1	77
	.40	11.3	76
	.50	12.2	75
	.60	13.5	74
	.70	13.4	69
	.80	13.5	57
	.90	12.5	53
Separan AP30	.05	2.2	43
	.10	3.9	45
	.20	4.5	51
	.30	4.7	42
	.40	5.8	43
	.50	7.2	40
	.60	8.1	41
	.70	8.8	43
	.80	10.2	41
	.90	10.5	41
	1.00	11.4	40
	1.10	11.7	41
	1.20	11.7	41
	1.30	12.0	67
	1.40	9.8	94
	1.50	9.7	92
Separan MGL	.25	12.6	84
	.50	13.7	93
	.75	13.9	95
	1.00	15.4	99
	1.25	16.8	98
	1.50	16.1	96
	1.75	15.5	93
	2.00	14.5	93
	2.50	14.7	96

Flocculant Used	Flocc Loading lbs/ton	Settling Rate cm/min	Clarity-Percent Transmittance
Separan C90	.05	1.8	59
	..25	2.9	71
	1.00	3.3	80
	4.00	3.3	65
Separan C-90 & AP30 in 3.5/1 Ratio	.25	5.3	71
	.50	6.1	78
	1.00	6.7	90
1:1 Ratio AP30/C90	1.00	8.4	90
	2.00	8.7	93
	4.00	13.8	97
	8.00	34.6	99
Superfloc 20	.05	9.3	66
	.10	12.0	74
	.30	13.9	88
	.50	14.6	92
	.70	15.2	92
	.90	15.8	97
	1.10	16.5	99
	1.30	16.8	96
	1.50	17.0	99
	1.70	18.5	97
	2.00	19.5	99
	3.00	14.9	94
	4.00	14.9	93
	8.00	16.9	83
Primafloc C-7	.50	10.5	89
	1.00	11.1	89
	1.50	12.3	72
	2.00	13.8	56
	2.50	13.6	22
	4.00	6.2	29
	8.00	10.1	16
	14.00	8.2	4
Sedomax F	.25	1.3	43
	1.00	1.0	24
	4.00	0.8	3
	16.00	no interface	

Flocculant Used	Flocc Loading lbs/ton	Settling Rate cm/min	Clarity-Percent Transmittance
Lytron 886	.50	no interface	-
	2.00	no interface	-
IX Glue	1.00	2.4	88
Lytron/Glue Ratio 1:1	1.00	3.9	25
	2.00	5.5	29
Ratio 3.5:1	1.00	2.8	60

APPENDIX II

TABULATION OF HYDROCYCLONE TEST RESULTS

PART A TABLE I

Slurry: Kaolin, 5% Solids, Unflocculated.

Observations						Calculated Results	
Feed Pressure psi	Wet Wt U. F. gms	Wet Wt O. F. gms	Dry Wt U. F. gms	Dry Wt O. F. gms	Sample Time Seconds	Flow Rate litres/min	Thickening Efficiency Percent
5	708	1205	58.2	49.3	15.75	7.0	27.9
10	663	1154	54.9	40.0	10.75	9.8	34.3
15	658	1150	55.4	36.6	9.0	11.7	38.2
20	642	1133	55.1	33.6	7.8	13.2	41.4
25	673	1191	58.5	34.2	7.0	15.5	43.1
25	637	1016	56.1	30.1	6.3	15.3	43.9
20	738	1169	62.9	36.4	8.1	13.7	41.0
15	633	1015	52.8	33.1	8.0	12.0	38.2
10	661	1038	50.0	34.7	9.85	9.9	33.5
5	714	1073	50.8	39.3	14.95	6.9	28.0

PART B

TABLE I

Slurry: Same as used in test shown in Table I, Part A, except flocculated.

Flocculant: 1. 0 gpl solution of Separan MGL injected 7 inches upstream from Point "O" (Refer Figure 11).

Target Flocculant Addition Rate: 0. 4 lbs/ton solids.

Observations							Calculated Results		
Feed Press psig	Flocc Addition l/min	Wet Wt U. F. gms	Wet Wt O. F. gms	Dry Wt U. F. gms	Dry Wt O. F. gms	Sample Time Seconds	Flow Rate l/min	Thick Eff %	Flocc Addition lbs/ton
5	. 073	751	'1148	78. 6	18. 8	16. 2	6. 8	68. 7	0. 40
5	. 073	789	1204	80. 9	24. 4	16. 75	6. 9	62. 4	0. 39
10	. 102	699	1090	71. 1	20. 3	9. 95	10. 4	64. 3	0. 37
10	. 102	698	1091	69. 9	16. 3	10. 8	9. 7	69. 6	0. 43
15	. 122	740	1150	70. 6	17. 9	9. 6	11. 5	67. 4	0. 44
15	. 1 22	759	1190	73. 8	19. 8	9. 7	11. 7	66. 0	0. 42
20	. 139	686	1086	57. 9	13. 3	7. 8	13. 3	70. 0	0. 51
20	. 139	800	1263	76. 8	21. 5	9. 0	13. 4	61. 7	0. 43
25	. 159	690	1101	69. 6	18. 7	7. 15	14. 6	64. 9	0. 42
25	. 159	807	1278	77. 2	18. 8	8. 0	15. 2	66. 2	0. 43
20	. 139	725	1149	69. 4	21. 8	8. 4	13. 0	68. 7	0. 44

PART A TABLE II

Slurry: Kaolin, 5% solids

Flocculant: 0. 5 gpl solution of Separan MGL injected at Point "A" (Refer Figure II).

Feed Pressure: constant at 20 psig.

Observations						Calculated Results		
Flocc Addition l/min	Wet Wt U. F. gms	Wet Wt O. F. gms	Dry Wt U. F. gms	Dry Wt O. F. gms	Sample Time Seconds	Flow Rate l/min	Thick Eff %	Flocc Addition lbs/ton
. 39	762	1299	90. 3	18. 5	8. 9	13. 5	73. 6	0. 53
. 39	775	1314	92. 7	15. 1	8. 8	13. 8	78. 3	0. 53
. 77	703	1242	80. 6	14. 9	8. 5	13. 3	76. 1	1. 15
. 77	708	1246	82. 6	16. 0	8. 2	13. 9	75. 2	1. 07
. 77	758	1335	90. 9	17. 1	8. 7	14. 0	75. 8	1. 04
1. 55	680	1264	55. 9	35. 0	8. 4	13. 5	42. 0	2. 38
1. 55	666	1208	61. 7	31. 7	7. 8	14. 0	48. 1	2. 15
1. 55	739	1359	63. 6	36. 7	8. 9	13. 7	44. 2	2. 29
. 77	673	1204	74. 2	15. 1	8. 0	13. 7	74. 2	1. 15

PART B

TABLE II

Slurry: Kaolin, 5% solids

Flocculant: 0. 5 gpl solution of Separan MGL injected at Point "B" (Refer Figure 11).

Feed Pressure: Constant at 20 psig

Observations						Calculated Results		
Flocc Addition l/min	Wet Wt U. F. gms	Wet Wt O. F. gms	Dry Wt U. F. gms	Dry Wt O. F. gms	Sample Time Seconds	Flow Rate l/min	Thick Eff %	Flocc Addition lbs/ton
0	514	924	49. 3	29. 4	6. 0	13. 9	44. 4	---
0	686	1254	64. 0	38. 9	8. 1	13. 9	43. 5	---
. 77	642	1105	78. 1	13. 7	6. 7	15. 1	77. 5	0. 92
. 77	697	1218	81. 4	14. 1	7. 9	14. 1	77. 8	1. 05
. 39	772	1324	89. 7	17. 7	8. 6	14. 2	75. 0	0. 50
. 39	786	1358	89. 3	17. 1	8. 9	14. 0	75. 7	0. 53

PART C TABLE II

Slurry: Kaolin, 5% solids

Flocculant: 0. 5 gpl solution of Separan MGL injected at Point "C" (refer Figure II).

Feed Pressure: Constant at 20 psig.

Observations						Calculated Results		
Flocc Addition l/min	Wet Wt U. F. gms.	Wet Wt O. F. gms	Dry Wt U. F. gms	Dry Wt O. F. gms	Sample Time Seconds	Flow Rate l/min	Thick Eff %	Flocc Addition lbs/ton
--	792	1325	70. 1	39. 0	8. 7	14. 2	43. 6	--
--	816	1370	69. 9	39. 0	8. 9	14. 3	43. 6	--
1. 12	774	1364	87. 2	22. 6	8. 4	14. 4	68. 4	1. 46
1. 12	748	1308	85. 1	21. 6	8. 0	14. 9	68. 9	1. 39
0. 74	688	1169	82. 7	14. 0	7. 3	14. 8	77. 6	0. 94
0. 74	726	1237	84. 5	14. 5	7. 9	14. 4	77. 3	0. 99
0. 37	767	1288	86. 4	18. 2	8. 6	13. 9	72. 9	0. 51
0. 37	724	1215	80. 8	16. 1	7. 7	14. 7	74. 1	0. 49
1. 65	713	1318	65. 4	26. 9	8. 3	14. 3	55. 7	2. 48

PART D

TABLE II

Slurry: Kaolin, 5 percent solids.

Flocculant: 1.0 gpl solution of Separan MGL injected at Point "O" (refer Figure 11).

Feed Pressure: Constant at 20 psig.

Observations						Calculated Results		
Flocc	Wet Wt		Dry Wt		Sample	Flow	Thick	Flocc
Addition	U. F.	O. F.	U. F.	O. F.	Time	Rate	Eff	Loading
l/min	gms	gms	gms	gms	Seconds	l/min	%	lbs/ton
.137	780	1268	90.8	17.5	9.0	13.3	76.0	.39
.205	806	1318	93.7	15.1	9.2	13.5	77.9	.58
.244	797	1316	93.1	14.5	9.0	13.7	86.8	.70
.328	727	1215	85.4	13.4	8.6	13.2	80.8	.98
.328	752	1259	84.1	12.9	8.5	13.8	81.2	.99
.244	728	1216	79.9	11.6	8.5	13.4	82.3	.78
.205	697	1161	77.8	11.3	8.2	13.2	82.3	.65
.137	696	1138	76.7	13.2	7.9	13.5	78.9	.42

PART A

TABLE III

Slurry: Kaolin, 5 percent solids

Flocculant: 0. 144 litres/min of 1. 0 gpl Separan MGL solution introduced through injection tube at various points in feed line.

Feed Pressure: Constant at 20 psig.

Observations						Calculated Results		
Inject Point Inches*	Wet Wt U. F. gms	Wet Wt O. F. gms	Dry Wt U. F. gms	Dry Wt O. F. gms	Sample Time Seconds	Flow Rate l/min	Thick Eff %	Flocc Load lbs/ton
n. f.	708	1178	62. 7	33. 0	8. 5	12. 9	45. 6	--
n. f.	753	1265	64. 4	34. 2	9. 2	12. 8	45. 4	--
0	809	1316	97. 8	12. 9	10. 0	12. 3	81. 7	0. 43
0	717	1180	89. 1	11. 4	8. 9	12. 4	82. 2	0.42
7	706	1178	88. 7	10. 7	8. 5	12. 9	83. 2	0. 41
7	757	1250	83. 8	9. 5	9. 4	12. 4	84. 0	0. 48
14	719	1208	89. 3	13. 8	8. 5	13. 2	79. 6	0. 40
14	688	1166	73. 6	9. 3	8. 4	12. 9	82. 6	0. 49

* Distance upstream from Point "O" (Refer Fig. 11).

PART B TABLE III

Slurry: Kaolin, 5 percent solids.

Flocculant: 0. 143 litres/min of 2. 0 gpl Separan MGL solution introduced through injection tube at various points in feed line.

Feed Pressure: Constant at 20 psig.

Observations						Calculated Results		
Inject	Wet Wt		Dry Wt		Sample	Flow	Thick	Flocc
Point	U. F.	O. F.	U. F.	O. F.	Time	Rate	Eff	Load
Inches*	gms	gms	gms	gms	Seconds	l/min	%	lbs/ton
n. f.	793	1243	71. 1	37. 2	8. 7	13. 6	44. 4	--
n. f.	699	1097	58. 5	31. 8	7. 9	13. 2	43. 1	--
0	694	1089	85. 0	9. 5	8. 3	12. 5	84. 0	0. 84
0	785	1224	94. 4	10. 0	9. 8	12. 0	84. 7	0. 89
7	687	1062	79. 3	8. 0	7. 8	13. 0	85. 3	0. 85
7	735	1149	84. 2	8. 6	8. 4	13. 1	85. 2	0. 86
14	744	1175	86. 8	11. 6	8. 3	13. 5	81. 2	0. 80
14	732	1176	66. 2	8. 3	8. 2	13. 5	82. 3	1. 05

* Distance upstream from Point "O" (Refer Fig. 11).

PART C TABLE III

Slurry: Kaolin, 5 percent solids.

Flocculant: 0. 147 litres/min of 0. 5 gpl Separan MGL solution introduced through injection tube at various points in feed line.

Feed Pressure: Constant at 20 psig.

Observations						Calculated Results		
Inject Point Inches*	Wet Wt U. F. gms	Wet Wt O. F. gms	Dry Wt U. F. gms	Dry Wt O. F. gms	Sample Time Seconds	Flow Rate l/min	Thick Eff %	Flocc Load lbs/ton
n. f.	736	1160	63. 5	35. 3	8. 0	13. 8	42. 4	--
n. f.	742	1166	60. 5	34. 0	8. 2	13. 6	41. 9	--
0	726	1109	82. 3	13. 1	8. 3	12. 9	77. 8	0. 21
0	759	1168	86. 8	14. 4	8. 7	12. 9	77. 1	0. 21
7	775	1208	76. 2	19. 5	8. 7	13. 3	67. 2	0. 22
7	736	1149	73. 9	18. 2	8. 3	13. 3	68. 2	0. 22
14	736	1156	64. 2	17. 4	8. 1	13. 7	65. 7	0. 24
14	715	1122	55. 2	13. 6	7. 9	13. 7	68. 1	0. 28

* Distance upstream from Point "O" (Refer Fig. 11).

PART D TABLE III

Slurry: Kaolin, 5 percent solids.

Flocculant: 0.137 litres/min of 2.0 gpl Separan MGL solution introduced through injection tube at various points in feed line.

Feed Pressure: Constant at 20 psig.

Observations						Calculated Results		
Inject Point Inches*	Wet Wt U.F. gms	Wet Wt O.F. gms	Dry Wt U.F. gms	Dry Wt O.F. gms	Sample Time Seconds	Flow Rate l/min	Thick Eff %	Flocc Load lbs/ton
0	661	1062	79.2	9.7	8.0	12.5	82.8	0.82
0	676	1090	80.1	9.0	8.0	12.7	84.1	0.83
2.5	606	1015	70.9	9.9	7.3	12.9	80.9	0.83
2.5	664	1106	76.3	11.1	8.1	12.7	80.2	0.85
5.0	643	1052	72.1	9.2	7.7	12.8	82.2	0.87
5.0	677	1113	72.8	9.6	8.2	12.8	81.7	0.90
7.5	627	1018	65.4	8.4	7.4	13.1	82.0	0.91
7.5	679	1099	69.6	9.2	8.1	12.9	81.5	0.93
10	684	1112	69.5	9.1	8.0	13.2	81.7	0.92
10	685	1020	68.6	8.9	8.3	12.8	81.9	0.97

* Distance upstream from Point "O" (Refer Fig. 11)

PART A TABLE IV

Slurry: Kaolin, 5% solids.

Flocculant: 0. 274 litres/min of 1. 0 gpl Separan MGL solution simultaneously added at Point "C" and 7 inches upstream from Point "O".

Feed Pressure: Constant at 20 psig.

Observations						Calculated Results		
	Wet Wt		Dry Wt		Sample	Flow	Thick	Flocc
Flocc Ratio*	U. F. gms	O. F. gms	U. F. gms	O. F. gms	Time Seconds	Rate l/min	Eff %	Load lbs/ton
1:1	858	1382	92. 3	21. 0	9. 9	13. 2	70. 6	0. 80
2:1	713	1155	72. 8	18. 5	8. 1	13. 4	67. 8	0. 81
2:1	710	1146	73. 8	18. 9	8. 2	13. 2	67. 6	0. 81
3:1	711	1151	68. 8	17. 4	8. 1	13. 4	68. 0	0. 86
3:1	666	1085	64. 5	15. 7	7. 7	13. 3	69. 0	0. 88

* Ratio - Flocculant added at "C": Flocculant added near cone.

PART B TABLE IV

Slurry: Kaolin, 5% solids.

Flocculant: 0. 274 litres/min of 2. 0 gpl Separan MGL solution simultaneously injected at Point "A" and at Point "O".

Feed Pressure: Constant at 20 psig.

	Observations					Calculated Results		
	Wet Wt		Dry Wt		Sample	Flow	Thick	Flocc
	U. F.	O. F.	U. F.	O. F.	Time	Rate	Eff	Load
Ratio*	gms	gms	gms	gms	Seconds	l/min	%	lbs/ton
0:4	682	1148	75. 5	16. 1	7. 9	13. 5	72. 6	1. 58
0:4	674	1139	74. 4	15. 8	8. 0	13. 3	72. 7	1. 61
3:1	651	1102	68. 2	14. 2	7. 5	13. 6	73. 2	1. 66
3:1	672	1145	68. 5	14. 6	8. 0	13. 3	72.3	1. 75
1:3	696	1219	59. 6	27. 0	8. 2	13. 7	51. 7	1. 72
1:3	734	1264	67. 7	24. 7	8. 4	13. 9	58. 4	1. 66

* Ratio - Flocculant added at "A": Flocculant added at "O".

TABLE V

Slurry: Kaolin, 5% solids.

Feed Pressure: Constant at 20 psig.

Dispersant: 0. 1 gms of a surfactant type of wetting agent* per litre of slurry.

Note: Samples 1 & 2 taken before dispersant was added.

	Observations					Calculated Results	
	Wet Wt		Dry Wt		Sample	Flow	Thick
Sample No.	U. F. gms.	O. F. gms	U. F. gms	O. F. gms	Time Seconds	Rate 1/min	Eff %
1	751	1174	60. 9	37. 1	7. 9	14. 2	36. 0
2	850	1330	68. 4	41. 8	8. 5	14. 9	38. 5
3	783	1230	59. 1	36. 7	8. 3	14. 1	37. 9
4	681	1080	49. 7	32. 7	7. 2	14. 3	36. 0
5	725	1148	51. 7	34. 5	7. 6	14. 4	35. 3
6	795	1261	56. 4	39. 7	8. 4	14. 1	33. 3
7	713	1145	54. 6	34. 5	7. 8	13. 9	37. 8
8	643	1034	47. 5	31. 0	6. 8	14. 4	36. 6

* Brand name Palconate, manufactured by Pacific Paper Co. of Chicago.

TABLE VI

Slurry: Silica*, 5% solids.

Flocculant: 0. 1 gpl Separan MGL solution injected at Point "O".

Feed Pressure: Constant at 20 psig.

Observations						Calculated Results		
Flocc	Wet Wt		Dry Wt		Sample	Flow	Thick	Flocc
Addition l/min	U. F. gms	O. F. gms	U. F. gms	O. F. gms	Time Seconds	Rate l/min	Eff %	Load lbs/ton
nil	795	1169	89. 6	12. 5	8. 2	14. 0	79. 9	--
nil	792	1151	89. 7	12. 2	8. 1	13. 9	80. 3	--
nil	768	1116	86. 7	12. 1	7. 7	14. 3	79. 9	--
0. 073	841	1243	98. 3	6. 6	9. 0	13. 5	89. 7	0. 21
0. 073	861	1250	99. 1	6. 2	8. 1	13. 5	90. 3	0. 21
0. 217	790	1216	86. 0	9. 9	9. 0	13. 0	83. 4	0. 68
0. 217	740	1138	79. 3	8. 8	8. 3	13. 2	83. 9	0. 68

* Ottawa Sand ground in ball mill for 30 hours.

Size Analyses by hydrometer method was as follows:

Stokesian Diam. - Microns	% Finer Than	Stokesian Diam. - Microns	% Finer Than
75	99. 8	14	27. 3
52	90. 2	12	24. 1
44	80. 2	11	20. 9
39	73. 8	9	15. 6
32	63. 8	7. 5	11. 6
25	48. 9	7. 0	10. 8
21	38. 9	5. 8	8. 8
17	32. 9	1. 6	1. 6

APPENDIX III

COMPARISON BETWEEN CALCULATED AND MEASURED D_{50} SIZE

D_{50} Size Determination

A simultaneous cut of the overflow and underflow discharge was made between Samples 7 and 8 shown on Table V. The size analysis of each of the discharges was carried out by the hydrometer method. The results are as follows:

Overflow		Underflow	
Stokesian Diam. - Microns	Percent Finer than	Stokesian Diam. - Microns	Percent finer than
68	100	69	98.8
40	99	33	95.6
17.5	95.4	17	89.1
12.3	93.3	12.3	74.6
9.3	88.2	9.5	64.5
6.6	78.6	6.8	47.6
4.6	61.2	5.0	33.1
3.6	52.0	3.8	25.8
3.1	39.3	3.2	19.8
2.6	34.7	2.5	16.5

From the size analyses of the two products and the relative weights of the two products taken from the average of samples 7 and 8, the classification distribution was determined. The classification distribution, often termed efficiency, was as follows:

Size Fraction - (Microns)	% to Underflow
-20 + 16	82
-16 + 12	81
-12 + 10	81
-10 + 8	79
-8 + 7	76
-7 + 6	70
-6 + 5	60
-5 + 4	51
-4 + 3. 5	43
-3. 5 + 3. 0	36
-3. 0 + 2. 5	39

As seen from the results shown above, the D_{50} size is about 4. 4 microns. This value can be roughly checked by referring to the size analyses of the kaolin. From the results for samples 7 and 8 the mass fraction of solids which reported to the overflow is 39 percent. Assuming that the amount of minus D_{50} size material found in the underflow is equal to the amount of plus D_{50} size material in the overflow, then 39 percent of the material should be finer than the D_{50} size. From Figure 9 it is seen that this corresponds to 4.7 microns, which is in fairly close agreement with the value determined above.

Theoretical Calculation of D_{50} Size

Using the flow data for Samples 7 and 8 of Table V, the D_{50} size was calculated according to the Lilge method. The calculations are as follows:

Bulk Inlet Velocity

$$V_i = \frac{Q}{A_i} = \frac{14.1\ \ell/\text{min} \times 144\ \text{in}^2/\text{ft}^2}{28.3\ \ell/\text{ft}^3 \times 0.125^2\ \pi\ \text{in}^2 \times 60\ \text{sec/min}}$$

$$= 24.4\ \text{ft/sec}$$

Velocity at Radius of Entry

$$\frac{V_{te}}{V_i} = \beta = 5.31 \left(\frac{A_i}{A_c}\right)^{0.565} = 5.31 \left(\frac{0.25^2}{1.25^2}\right)^{0.565}$$

$$= 0.859$$

$$V_{te} = 24.4 \times 0.859 = 21.0\ \text{ft/sec}$$

Tangential Velocity at Radius of Maximum Tangential Velocity

Radius of V_t = max., $= \frac{R_c}{6} = 0.104$ in.

Radius of entry $= R_c - R_i = 0.5$ in.

Assuming $n = 0.8$

$$V_t = \text{max.} = V_{te} \left(\frac{R_e}{R_t}\right)^{0.8} = 21.0 \left(\frac{0.5}{0.104}\right)^{0.8}$$

$$= 73.6\ \text{ft/sec}$$

Radial Velocity at Intersection of Envelope of Maximum Tangential Velocity and Envelope of Zero Vertical Velocity

$$V_R = \frac{2.219\, Q_o}{D_c h} = \frac{2.219 \times 0.1464\ \ell/\text{sec}}{\frac{7.0 \times 1.25}{144} \times 28.3\ \ell/\text{ft}^3}$$

$$= 0.187\ \text{ft/sec}$$

D_{50} Size

Assuming the particles are spheres and the flow relative to the particles is in the laminar regime the D_{50} size is calculated as follows:

$$D_{50}^{\ 2} = \frac{18\, \mu R V_r}{(\rho_s - \rho) V_t^{\ 2}}$$

substituting above values

$$D_{50}^{\ 2} = \frac{18 \times 6.7 \times 10^{-4} \times 0.104 \times 0.187}{(2.58 - 1.02) \times 62.4 \times 73.6^2 \times 12}$$

$$= 37.1 \times 10^{-12}\ \text{ft}^2$$

$$D_{50} = 6.09 \times 10^{-6}\ \text{ft}$$

In microns

$$D_{50} = 6.05 \times 10^{-6} \times 3.048 \times 10^5$$

$$= 1.86 \text{ microns spherical diameter}$$

Check Reynold's Number

$$Re = \frac{D_{50} V_r \rho}{\mu} = \frac{6.09 \times 10^{-6} \times 0.187 \times 63.6}{6.7 \times 10^{-4}}$$

$$= 0.108$$

Flow relative to particle is in laminar regime as originally assumed.

Results

D_{50} size determined experimentally is 4.4 microns, D_{50} size calculated for prevailing flow conditions is 1.86 microns. Experimentally determined size is 2.4 times greater than the calculated value.